THE MECHANISM OF DROPWISE CONDENSATION OF STEAM.

A Thesis Submitted for Ph.D. Examination

in the

Queen Mary College

University of London.

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June,1949.

Acknowledgement.

The writer wishes to express his humble appreciation to the Department of Scientific and Industrial Research whose generous financial help has made this work possible. Hearty thanks are also due to Professor E. Giffen, M.Sc., Ph.D., D.Sc., M.I.Mech.E. and Mr. H. Hampson, M.Sc., M.I.Mech.E. for their enthusiastic guidance and encouragement throughout this work.

CONTAINS PULLOUTS

THE MECHANISM OF DROPWISE CONDENSATION OF STEAM

Contents

Pictures and Graphs, unless they appear closely with the text when they are referred to, will be found at the end of each chapter.

THE MECHANISM OF DROPWISE CONDENSATION OF STEAM

Abstract:

The present investigation can be divided into two parts: (a) experiments made to examine the mechanism of dropwise condensation of steam with particular reference to the stability of drop promoting surfaces as affected by the material of cooled surface, the drop promoter, the surface finish, the rate of heat transmission, and the presence of non-condensable gas; and (b) a theoretical analysis of the heat transmission through individual droplets, the transient heat transfer through exposed areas, the statistical study of drop size distribution, and the estimation of steam side coefficient.

An apparatus was developed to examine qualitatively the behaviour of drop promoting surfaces on a small scale. It is considered that sufficient evidence was found to show that steam in contact with a cooled surface condenses as a thin liquid film which later breaks into droplets. Surfaces treated to give dropwise condensation deteriorate into mixed condensation in due time, and the duration for which a treated surface maintains dropwise condensation

varies between a few hours to several days, depending on many factors among which the presence of non-condensable gas must not be overlooked.

An approximation to the heat transmission through individual droplets has been worked out with assumed heat flow lines. The result, checked by the relaxation method, is correct within +10%. An analysis of the transient heat transfer through exposed areas was made neglecting the increasing resistance of any accumulating liquid. The drop size distribution was analyzed for one drop promoting surface at three different heat transmission rates. Based on this drop size distribution, the heat transmission through the drops was estimated by assuming they were held at rest on a cooled surface conducting heat under a steady state. The estimated coefficient comes within the range of experimental results of many investigators.

CHAPTER 1.

INTRODUCTION AND SUMMARY

The investigation of heat transmission in the process of condensation of steam on a cooled surface arises in connection with power plant condensers and evaporators. It is different from the usual process of heat exchange between a fluid and a metal surface which involves no change of physical state of the fluid, in the fact that heat transmission in the process of condensation is accompanied by the formation of condensate. The condensate formed on the cooled surface constitutes a resistance to heat flow. Therefore the coefficient of heat transfer in the process of condensation depends much on the manner in which the condensate is formed and taken away.

On a wettable surface the condensate exists as a thin, continuous liquid film over the entire surface, while on a non-wettable surface the condensate exists in the form of numerous discrete droplets which grow and coalesce to form bigger drops until they roll off by gravity. In the latter case the coefficient of heat transfer can be 20 or 30 times

higher than in the former one. The difference is so big that they are generally regarded as two different types of condensation. The former is known as filmwise condensation, and the latter, dropwise condensation. It is understood that the cooled surface may be, and usually is in practice, in such a condition that dropwise condensation occurs on some parts of the surface while filmwise condensation takes place on other parts. This is known as mixed condensation.

For filmwise condensation, a theoretical equation has been developed by Nusselt [22] by which the coefficient of heat transfer can be predicted from the temperature difference between the vapour and the cooled surface, certain physical properties of the condensate, and the vertical dimension of the cooled surface. In the case of horizontal tubes and short vertical surfaces, Nusselt's theoretical value agrees well with experimental results as shown by various investigators [12, 13, 19, 26, 31]. For long vertical surfaces, experimental results show considerable deviation from Nusselt's theoretical value. It is generally accepted that this is due to the effect of turbulence developed in the condensate layer on the lower part of the vertical surface where the Reynold's number is high. In this case, however, several investigators [2, 16] showed that the

experimental data can be correlated by empirical equations involving such dimensionless terms as suggested by Nusselt's theoretical equation. A semi-theoretical treatment of the effect of turbulence was given by Colburn [6].

On the other hand, comparatively less is known about dropwise condensation. The conditions under which dropwise condensation takes place have been studied by many earlier investigators [13, 15, 25, 30], but they remained, nevertheless, only imperfectly known until Drew, Nagle, and Smith [7] proved that dropwise condensation does not occur even on highly polished surfaces unless the surface is in some way contaminated. In fact, they found that by using suitable promoters, a cooled metal surface can be induced to give dropwise condensation. Subsequent experiments to determine the coefficients of heat transfer for dropwise condensation were generally performed on surfaces promoted with suitable drop promoters such as long chain fatty acids, mercaptans, and so on. The measured coefficients of heat transfer reported by several investigators varied over a rather wide range, between 5,000 and 20,000 B.t.u./ft^2-hr-°F, and is apparently independent of heat load. Since for dropwise condensation, the temperature drop between the cooled surface and the steam is usually small, and furthermore the local surface temperature shows more or less

periodic fluctuations, it would be expected that there is some uncertainty in ascertaining the temperature drop and hence the heat transfer coefficient.

In view of the practical importance and also the academic interest arising from dropwise condensation, a research programme is being carried out on this subject in Queen Mary College, University of London, in collaboration with the Department of Scientific and Industrial Research. The initial stage of this research was pursued along two lines of investigation. One phase of the research deals with the experimental determination of the rate of heat transfer on the vapour side during condensation. The present work represents another phase of the research and aims to investigate the mechanism of dropwise condensation.

One interesting aspect in the mechanism of dropwise condensation is the way in which the microscopically small droplets which appear abruptly on the exposed areas of the cooled surface are originated. For instance, do the tiny droplets originate from nuclei on the surface, or does the steam condense in a thin layer of water film which later on breaks into droplets? In the course of the present investigation some interference fringes were observed on newly

exposed areas of a polished surface on which dropwise condensation was taking place at a very much reduced rate. This phenomenon is considered to bear considerable significance as it reveals the existence of a thin layer of liquid film of varying thickness which breaks into droplets. The same observation was also reported by Old [23].

Since the condition of the cooled surface is the predominant factor in determining the type of condensation, it is essential that the surface must be carefully treated in order to get one or other type of condensation. In addition, it is also known that a treated surface which gives dropwise condensation initially is subjected to further changes as condensation goes on. A knowledge of the behaviour of drop promoting surfaces would be advantageous to future experimental work in this field. In view of the lack of this knowledge in literature, part of the present work was undertaken to investigate the stability of dropwise promoting surfaces in relation to the material of the surface, the drop promoter, the surface finish, the rate of condensation, and the presence of non-condensable gas. Among these variables, the presence of non-condensable gas deserves special mention as its important influence upon the stability of drop promoting surfaces is not generally appreciated.

The later part of the present work deals with the theoretical side of the heat transmission in the process of dropwise condensation. In its analysis, the steam side resistance and the resistance of the metal plate are conveniently combined together as a non-separable whole. The water side surface of the plate is assumed to be at a constant temperature. The steam side surface temperature is not considered to be constant, but varies locally, depending on whether the local surface is exposed to steam, or, if covered by a droplet, the size of the droplet. A mathematical analysis has been made on the heat transmission through individual droplets with arbitrarily assumed heat flow lines. The result, when checked by means of the relaxation method, is found to be correct to within 10%. Also the statistical drop size distribution was analyzed for one drop promoting surface at 3 different heat transmission rates. Taking drops from maximum size down to a lower limit of 0.005 inch diameter which is the smallest that can be resolved accurately with the present techniques, it was found that the area covered by such drops is approximately 55% of the whole surface. Based on this statistical drop size distribution and the heat transmission through droplets, a steam side coefficient was worked out which falls within the range of experimental results.

CHAPTER 2.

REVIEW OF THE PREVIOUS WORKS

The important significance of dropwise condensation was first recognized, independently, by Schmidt, Schurig, and Sellschopp [25] in Danzig and Speelstra [30] in Java. They found that the overall coefficient of heat transfer is several times higher when condensation is dropwise that when it is filmwise. This discovery aroused much interest and opened a new field of investigation. For if dropwise condensation can be maintained, then it is quite possible to increase the efficiency of a condenser two- or threefold, much more than could be achieved with any reasonable improvement on the water side.

The fact that steam may condense in drops had been known for some time, although its significance was not fully appreciated. In 1897 Callendar and Nicolson [5] concluded that "the drops of condensed water with which the surface is partially covered are in such rapid motion that they do not appreciably obstruct the passage of heat from the steam to the metal." They further remarked that "the viscosity of water

at these temperatures is so small and the motion so rapid, that the drops cannot be treated as a quiescent film."

In an investigation of the heat transfer coefficients during the condensation of steam, Schmidt et al built an apparatus in which a glass window was incorporated to permit the observation and photography of the condensation process. Preliminary trial with a smooth copper surface of no specific treatment showed that the condensate did not exist as a continuous film as was expected. Instead it formed tiny droplets, nearly semi-spherical in shape, which grew by coalescence until they fell off under the influence of gravity. After prolonged condensation with unfiltered steam, parts of the surface were fouled and the condensate formed patches of film there. With the surface in this condition, the measurement of heat transmission gave widely scattered results. So they tried to make a distinction between condensation in film and that in drops and made the first attempts to treat the surface to make it give completely film or completely drops. They found that a copper surface etched by a soldering solution gave completely film. A light coating of petroleum on a copper surface gave completely drops, but this effect did not last long. A polished, chromium plated copper surface gave a lasting drop forming

effect. In film runs, the steam side coefficient agreed fairly well with Nusselt's theory. But condensation in drops gave coefficients 5 to 7 times higher. The overall coefficient under the latter conditions was increased three-fold with the highest available cooling rate of the water side.

Meanwhile Spoelstra made a series of experiments on the performance of evaporator tubes following some cleaning and polishing of the fouled tubes. His original paper, being published in Dutch, was reviewed by Nagle and Drew [21]. In his experiments on 1m. long tubes, the overall coefficients were observed, but the condensation process was not visible. The results can be briefly summarized as follows:

(1) A used evaporator tube became less efficient after being washed with naphtha. Further analysis showed that the original scale contained 15 to 30% oily substance which was largely removed by the naphtha.

(2) When a used evaporator tube was removed of its scale, polished, and finally washed in naphtha, it became less efficient if the original scale was oily, but more efficient if the original scale was comparatively oil-free.

(3) The injection of oil into the steam caused a marked increase in the overall coefficients for 1) a clean,

uncorroded tube and 2) a tube slightly fouled but made oil free. But for 1) an entirely clean but severely pitted tube and 2) a badly fouled tube, the injection of oil showed no marked effect.

Later Spoelstra made condensation experiments inside a glass flask with short test-lengths cut from the tubes examined previously, so that the type of condensation could be seen. The results, summarized by Spoelstra, were as follows:

(1) On a clean copper or brass tube, either type of condensation can take place:- filmwise, dropwise, or mixed. The form of condensation cannot always be predicted with certainty. The general tendency is that filmwise condensation is to be expected on somewhat rough or scratched surfaces and dropwise condensation on smooth, well polished surfaces.

(2) By scouring it with fine emery cloth, a clean tube which gave dropwise condensation previously can be made to give filmwise condensation. On the addition of a little oil, this filmwise condensation returned to dropwise condensation.

(3) Tubes with a porous (oil-free) scale always exhibit filmwise condensation. By means of oil injection this filmwise condensation can be changed entirely or partially to dropwise condensation.

(4) Tubes which are so badly fouled that their surface is uneven and rough always exhibit filmwise condensation. In general it is not possible to obtain dropwise condensation in this case by oiling.

(5) Various appearances of dropwise condensation may be recognized. In general the best types of dropwise condensation occur on very smooth and at the same time oily surfaces.

Jakob [13] quoted the experiments of Roecke who observed dropwise condensation with saturated and also with superheated steam. With superheated steam the droplets adhered longer, became flattened down and broadened, thus covering a larger area than the more rapidly growing droplets from saturated steam so that a greater resistance to heat transmission was produced. Also droplets appeared much more slowly on areas previously swept over by falling drops. These effects were more pronounced with increased degrees of superheat. His investigations included the use of a cine-camera.

In reviewing the experimental investigations of the conditions governing the type of condensation, Jakob [13] wrote that dropwise condensation occurs invariably with greasy, non-wettable surfaces, and filmwise condensation with

rough surfaces, but both also with clean polished surfaces. Regarding the last case, he suggested that the direction and speed of the vapour were the decisive factors. He quoted some experiments which showed indirectly that a state of rest and slow motion of the vapour at right angles to the cooled surface appeared to be conductive to dropwise condensation, while rapid motion parallel to the cooled surface conductive to filmwise condensation.

Jeffrey and Moynihan [15] found that a commercially clean elytrolytic copper condenser tube normally gave dropwise condensation. A monel metal tube in "as received" condition, which had been in service for 25 years and was coated on its outside with a thin layer of scale, gave completely filmwise condensation. After the outside of this tube was cleaned, condensation took place under drop formation. However they believed that in actual use, as a "commercially" clean tube becomes covered on the outside with an oxide layer and particularly with a layer deposited by the impurities in the steam, the type of condensation gradually changes from drop to film form. Commenting on the reason why an etched metal surface gave filmwise condensation as reported by Schmidt et al, they stated that the effect was not that the surface was roughened, but that it removed the infinitesimally thin

greasy film with which all surfaces are naturally covered. And contrary to the opinion of some other observers, they found dropwise condensation does not require very highly polished surfaces, nor very slow vapour speed.

Nagle and Drew [21] made a comprehensive survey of the earlier investigations concerning the conditions of dropwise condensation. They, together with Smith [7], after making further clarifying experiments, made one controversal point quite clear:- that clean steam always condenses in a film on clean surfaces, whether rough or polished. Their technique for cleaning the metal surfaces was one or another of the following:

(1) Washing thoroughly with a boiling hot solution made up of soda ash, trisodium phosphate, soap, and caustic soda.

(2) Rubbing with precipitated chalk on a wetted cloth.

(3) Rubbing with powdered emery on a wetted cloth.

After cleaning, all metal surfaces showed complete filmwise condensation. This proved that the "clean" polished surfaces reported in literature to show persistent dropwise condensation were not really clean. Their other conclusions were:

(1) Dropwise condensation does not occur unless the cooled surface is in some way contaminated.

(2) Although numerous substances, while actually on the surface, will make it non-wettable, only those that are strongly absorbed or otherwise firmly held are significant as drop promoter. Some contaminants seem to depend for their activity as promoters on the amount of non-condensable gas present.

(3) Dropwise condensation is induced and maintained more easily on smooth surfaces than on rough surfaces.

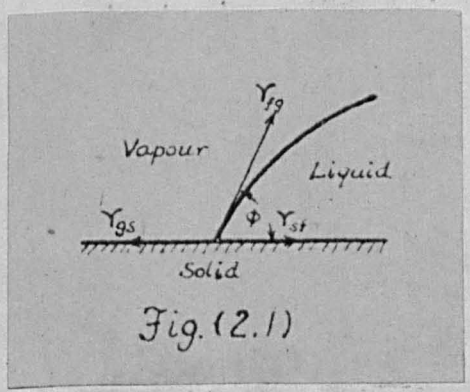


Fig.(2.1)

Emmons [8] explained the condition for dropwise condensation in terms of "spreading coefficient" $\mathcal{Z}$ defined as

$$\mathcal{Z} = \gamma_{gs} - \gamma_{fg} - \gamma_{sf}$$

where γ_{gs}, γ_{fg}, and γ_{sf} represent the interfacial tensions, Fig.(2.1). If $\mathcal{Z}$ is positive, the liquid will spread over the solid surface. If $\mathcal{Z}$ is negative, the liquid will withdraw from the solid surface until ϕ reaches an equilibrium value given by

$$\gamma_{sg} = \gamma_{sf} + \gamma_{fg} \cos \phi .$$

Hence the condition for filmwise condensation is $\mathcal{Z}$ be zero or positive while the <u>necessary</u> condition for dropwise

condensation is ζ be negative. The latter condition is not sufficient when the whole process of condensation is considered. The drops of liquid which form on the cooled surface grow, touch, and merge. If, after touching, two drops merge so slowly that other drops combine with them on all sides, the surface will soon be covered with a film (formed by the joining of the drops). From this point of view, the conditions favouring dropwise condensation are:- (1) low rate of condensation, (2) low condensate viscosity, (3) large negative value of spreading coefficient, and (4) smoothness of the cooled surface.

Regarding the drop promoters, Drew et al [7] tried a number of organic compounds on various metal surfaces, and classified them as "very effective", "ineffective", and so on. A compound was described as "very effective" if it produced dropwise condensation which lasted 24 hours or longer, "ineffective" if no dropwise condensation was induced following its application. The application of chemicals was either by injecting into the steam chamber or coating on to the surface. For the sake of providing a reasonable basis of comparison, the metal surface was always made clean, or in other word wettable, before test. The steam used was sometimes pure steam and sometimes boiler steam. Those classified

as "very effective" were:

Stearic acid	on copper brass, Cr-Ni steel;
Oleic acid	on copper, brass, Cr-Ni steel, chromium;
Linoleic acid	on monel metal;
Beeswax	on copper, Cr-Ni steel;
Benzyl mercaptan	on copper, brass, monel metal;
Potassium amyl xanthate	on copper, brass;
Dithiophosphates	on copper, brass.

Emmons [8] made similar experiments with some other chemicals and supplemented the date of Drew et al.

The effect of molecular arrangement on promoter action was discussed by Emmons [8]. It was postulated that for a chemical compound to be a successful promoter, its molecules require a relatively active radical connected to a relatively saturated radical and the molecules orient themselves on the cooled surfaces with their inactive end pointing to the condensing vapour. This consideration led him to the conclusion that one and only one layer of promoter molecules on the cooled surface could be responsible for dropwise condensation. He made experiments in which one or more molecular layers of stearic acid were deposited on initially clean surfaces. These tests did seem to verify his conclusion that one complete molecular layer is enough to

induce dropwise condensation, and all promoter molecules beyond one complete layer are removed immediately by the condensing steam. With a coating of 2 to 10 molecular stearate layers on a nickel surface, the initial dropwise condensation turned into filmwise within 5 to 10 minutes, apparently independent of the number of molecular layers originally coated. Also he examined the effect of small excesses of stearic acid in the steam on the duration of drop-wise condensation. The results seemed somewhat intangible: on copper the excess stearic acid caused dropwise condensation to last longer, while on nickel it appeared only to help remove that already on the surface. In some of his tests, a small amount of air was said to affect the results so that no consistent, reproducible results could be obtained.

The coefficients of heat transfer for dropwise condensation on vertical surfaces was measured by Schmidt, Schurig, and Sellschopp [25] ; Gnam [11] ; Nagle, Bays, Blenderman, and Drew [20] ; Fitzpatrick, Baum, and McAdams [10] ; Shea and Krase [26] . With saturated steam condensing on vertical surfaces between heights of 0.5ft and 10ft., most of the measured coefficients of heat transfer fall within the range between 5,000 and 20,000 B.t.u. /ft^2-hr-°F, although some much higher values were reported by Shea and Krase for 0.4ft high

surface. Furthermore the coefficient appears to be practically independent of heat load, over the range of heat load between 60,000 and 300,000 B.t.u. /ft²-hr, the highest heat load being limited by the rate of cooling. Recent experiments done in Queen Mary College on a 5" high by 3" wide surface attained still higher heat load, up to 430,000 B.t.u. / ft²-hr, and confirmed the small dependence of coefficient upon heat load over a wider range, the average coefficient 25,000 B.t.u. /Ft²-hr -°F being somewhat higher than the earlier results mentioned above. As has been remarked by M.Jakob (10), this independence of coefficient on heat load is most significant when it is compared with the case of filmwise condensation.

In dropwise condensation, the heating effect of superheated steam was found by Gnam (11) to be only slightly better than that of saturated steam at the same pressure. With 100°C. superheat, the steam side coefficient, based on the difference between the saturation temperature of steam and the temperature of the steam side surface, was only 3-4% higher than that of saturated steam.

It is generally realized that the extraordinarily high heat transfer coefficients for dropwise condensation compared with filmwise condensation are due to the fact that in dropwise

condensation the cooled surface is partially instead of completely covered by condensate. In so far as it is not clear what exactly happens in areas not covered by drops, various views have been put forward by several investigators. Thus Emmons (8), based upon the behaviour of molecules at surfaces, deduced that there exists a blanket of supersaturated vapour in the bare area between drops. Where this supersaturated vapour comes in contact with the surface of a drop, condensation takes place very rapidly, thus producing a local reduction in pressure which in turn sets up violent local eddy currents in the vapour between the drops. This mechanism is, according to Emmons, responsible for the very high heat transfer coefficient in dropwise condensation.

Jakob (14) suggested, however, that in the bared cooled surface, the particles of steam are held fast on the surface without forming a coherent film that would offer a considerable resistance to heat transmission. On the contrary, they form droplets at once and immediately free the surface. The surface can be considered as being covered by a very thin layer of steam or water which continually and quickly varies in thickness from nothing to a certain maximum thickness and contracts to form droplets, the layer being built up again by fresh steam. The average thickness of this unstable film was estimated from the steam side coefficient to be of the

order of 0.001 mm. It can be said that some observations made in the course of the present investigation would appear to support Jakob's view.

In dropwise condensation, it has always been difficult to determine the heat transfer coefficients with certainty. The difficulty, apart from the disturbances caused by introducing thermocouple junctions, also lies in the fluctuation of the steam side surface temperature. Jeffrey and Moynihan (15) soldered thermocouples on to the steam side surface and noted the couple readings varied over a range of approximately ± 2°C. in an erratic manner. It should be appreciated that this variation is nearly of the same order as the steam side temperature difference. Hence they pointed out that "it does not seem adequate in the measurement of surface temperatures simply to connect 2 or more thermocouples in the usual fashion, and then to regard the mean of the readings so obtained as the mean surface temperature of the entire surface. As long as dropwise condensation persists in any test this method may be subject to very considerable errors." Gnam (11) measured the temperature 0.5mm below the condensing surface and registered it on a piece of moving sensitive paper. He observed a more or less periodic fluctuation of temperature, the period varying between 0.5 and 5 seconds, depending on

the rate of condensation. Considering the constant covering and uncovering of local surface, it is clear that this temperature fluctuation is inherent to the steam side surface in dropwise condensation.

This leads to the conclusions:-

A survey of the previous investigations showed that much work had been done regarding the conditions governing the type of condensation. It seems clear that dropwise condensation does not take place unless the cooled surface is contaminated. Dropwise condensation can be induced, and maintained for some time on metal surfaces by suitable drop promoters, more readily if the surface is smooth and free of scale. However with prolonged condensation, as the cooled surface becomes fouled or the promoter is worn out, dropwise condensation no longer persists. The duration for which a promoted surface maintains dropwise condensation depends on the initial surface preparation and the quality of the steam and other factors none of which had been adequately investigated. No information was previously available as to the effect of the presence of a non-condensable gas on the duration of dropwise type of condensation on any surface.

Regarding the transmission of heat occurring during dropwise condensation, much work has been done to determine

the steam side coefficients, but an entirely satisfactory method of measuring mean surface temperature does not, as yet, seem to be in existence. With saturated steam at atmospheric pressure which passes the condensing surface with no substantial speed, the probable value of the coefficients seem to lie between 15,000 and 20,000 B.t.u./ft^2-hr-°F, and depend very little on the rate of condensation for short vertical surfaces. Theoretical considerations of the heat transmission process associated with dropwise condensation were scarcely touched by previous investigators.

CHAPTER 3

DESCRIPTION OF THE APPARATUS.

The purpose for which the present apparatus has been built is to examine generally the mechanism of dropwise condensation with special reference to the qualitative investigation of the stability of drop promoting surfaces under various operating conditions. With this object in view it requires that:-

(1) the apparatus must be easily kept in reasonable cleanliness so that clean steam can be generated to condense on a pre-treated surface free from, as much as possible, the interference of any fortuitous source of contamination,

(2) the apparatus be capable of providing a variety of experimental conditions and of operating under steady conditions for prolonged periods uninterruptedly,

(3) the drop formation can be observed visually and photographic records be taken periodically of the progress of the drop promoting surfaces.

Only qualitative investigations were intended in the present apparatus. No attempts were made to measure quantitatively the rate of condensation or the heat transfer coefficient.

A simple apparatus, not described here, was originally constructed and used in the preliminary stages of the present investigation. Its relatively simple construction prevented adequate control of the test conditions. However, the experience gained from it has been used to advantage in developing the present apparatus as described below.

Briefly, steam generated in a 3 l. pyrex flask is led to a similar flask where it is allowed to condense on a test surface cooled by running water. Necessary arrangements were made to provide the control and the measurement of the test conditions such as the temperature and pressure of the steam, the rate of cooling, the injection of drop promoter, and the injection of non-condensable gas, etc.

The test surface is a metal disc of 1 inch diameter. Preliminary trials on a simple apparatus indicated that a cooled surface of this size was large enough to show the effect of the surface treatment. Maximum drop size was of the order of 0.15 inch and spacing of this size of drop seldom

more than 0.5 inch. This small area did not always give a general impression similar to that given by a larger area, but the effect of surface treatment was reproduced.

The general arrangement of the apparatus is shown in Plate (3.1) and also diagrammatically shown in Fig (3.3). It consists of 3 sets of identical construction; two being used for normal experimental work and one maintained in as near chemically clean condition as possible so that check runs could be made periodically. Later the supply of adequate feed water to the boiler flasks was limited, the tests then being made in one set at a time, but time has been saved by getting the other sets ready while tests were being carried out in one set.

Plate (3.2) shows the close-up view of one set with some covers removed; the detail parts are shown in Fig (3.4). Referring to Fig (3.4), water is fed continuously into the flask (A) where steam is generated by a bunsen burner. The steam passes through the passage (H) and goes into the flask (B) wherein it is allowed to condense on the test surface (C). The test surface is soldered on to the end of the supporting tube (D) which carried the cooling water conduits, the latter being insulated from the outside of the supporting tube to reduce unwanted condensation. (M) and (N) are respectively

the inlet and outlet for the cooling water.

The pair of flasks are placed side by side in an asbestos sheet cabinet which is filled with the hot gas from the bunsen burner. This reduces heat loss and also prevents condensation on the flask wall so that the test surface can be clearly observed through the plate glass (K). The flasks are placed with their axes lying in a horizontal position so that the condensate dripping from the test surface will accumulate insids the flask (B) up to a certain level (about $\frac{1}{8}$ inch below the lowest point of the test surface), after which it is automatically removed with excess steam through port (J) into the auxiliary condenser.

An important feature is the way by which the flasks are closed. The top of the neck of the flask is ground to provide a ring of flat surface of about $\frac{1}{8}$ inch width. To this is clamped a scraped brass cover (P) by bolts (Q) to secure a tight joint. The brass tube (D) on which the test surface is attached can be withdrawn conveniently; the joint being made tight by a soft wire packing (S). On the steam passage (H) is a port (E) through which drop promoter or non-condensable gas can be introduced, but it is normally closed. It can be seen that from where the steam is generated to where it is condensed on the test surface, the steam comes in contact

only with brass and glass parts. These parts are easily accessible and therefore can be maintained in reasonable cleanliness.

The arrangement of all necessary piping systems and gauge lines are shown in Plate (3.1b) and also diagrammatically shown in Fig.(3.4). Referring to Fig (3.4), the excess steam and condensate from each set are led to a common auxiliary condenser (G) in which excess steam is condensed by running water. The steam pressure of each set is indicated by column (M). Under normal conditions, the pressure is kept to about 4 inches water above atmospheric pressure. The steam temperature is measured by mercury thermometers (T), and is generally adjusted to 1 to 2°C superheat. The rate of cooling on the water side (i.e. the flow of cooling water) is controlled by valves (P) and is indicated by pressure gauge (L). The feed water for flasks (A) is taken from a common feed line and regulated by cocks (W) to maintain a nearly constant water level.

The amount of steam which can be generated in this way is very limited. Care is taken that there is enough steam to fully load the test surface, especially at higher rates of cooling. Try-cock (N) - seen on top of the auxiliary condenser, Fig (3.3) - is provided to check whether there is

excess steam blowing out. Normally enough steam can be generated inside the boiler flask (A) only. At the highest cooling rates, it was necessary to supplement it by using another bunsen burner under the condenser flask (B). In the latter case care was taken that the test surface was not splashed.

The continuous supply of suitable feed water presented at one time considerable difficulty. Mains water was tried in the first place, but was found to deposit too much scale on the boiler flasks. Its dissolved air is another objection. The use of distilled water from the college boiler room involved constant labour, and it is doubtful whether it does not contain some dissolved air. The difficulty was finally overcome by the use of a small electrically heated distilling plant. It can be seen in Fig.(3.3) on the upper left. The distilled water from the still is stored in a closed bottle (C) while it is still hot, and it is then fed into the boiler flasks. Therefore it is reasonable to assume that the feed water is practically free of air. After prolonged periods of boiling with this feed water (say, after several days' continuous running) , some brown boiling marks were observed in the boiler flasks. This was found to be due to the rusty scale from the inner wall of the copper connecting tubes and also possibly from the iron parts of the still being carried over with the feed water. This scale is ignored in the

later experiments as it is not greasy, and very little of it was found to be carried over to the condensing chamber flask.

Before making tests, the whole interior was thoroughly cleaned with trichloroethylene and afterwards rinsed with water. After this, the interior parts were completely wettable with cold water. This was always done whenever a change in drop promoter was involved. If the same drop promoter was used in a series of experiments, the apparatus was only periodically cleaned.

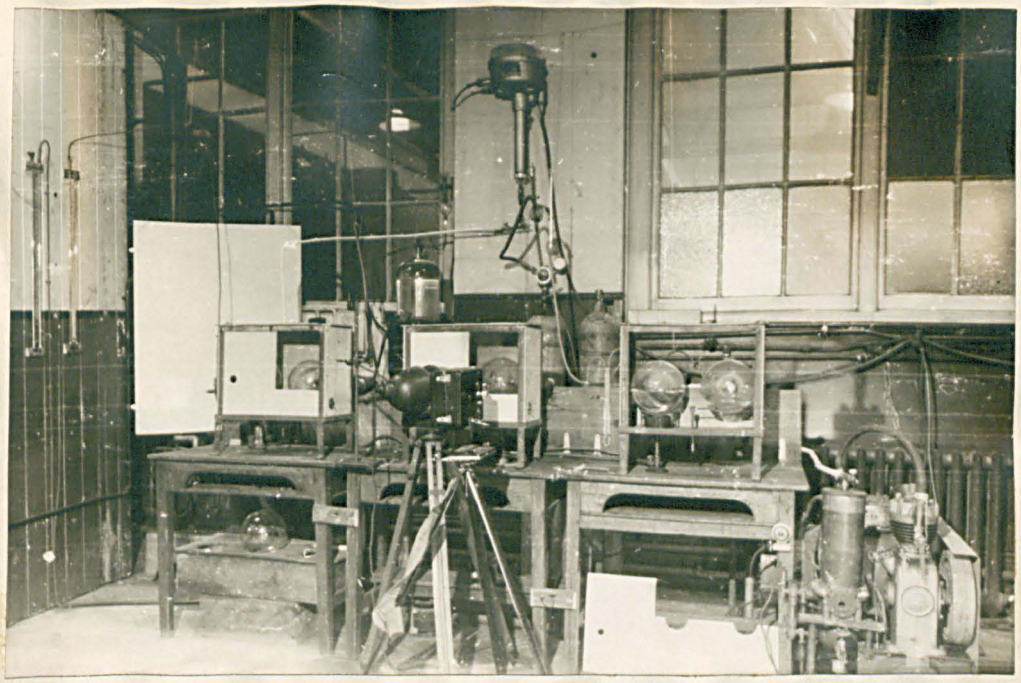
There is no limit to the possible variations of the materials of the cooled surface and the drop promoters. The present experiments were restricted to a ~~few~~ limited number of such combinations as were suggested in literature and also preferred by the present writer as inducing dropwise condensation readily. Materials chosen for the test surfaces were limited to brass, copper, stainless steel, and chromium plated copper. The drop promoters which were given trial were:

(1) oleic acid and benzyl mercaptan on brass and copper, and

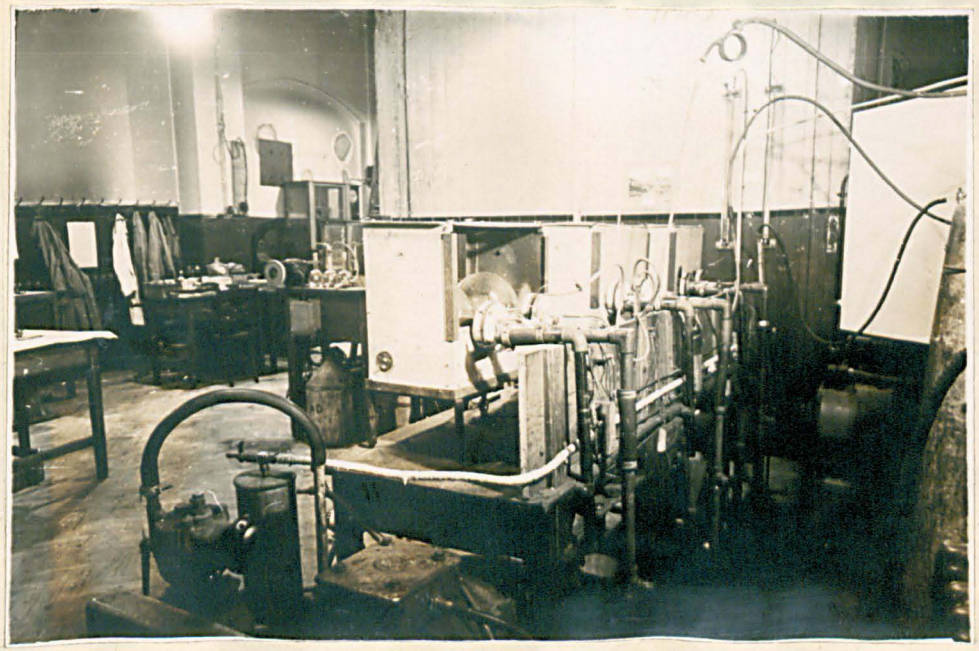
(2) mixture of oleic acid and small amount of a light lubricating oil on stainless steel and chromium. It was found that oleic acid mixed with a small amount of a light lubricating oil gives better looking dropwise

condensation than if oleic acid is used alone, and it is always preferred to treat stainless steel and chromium surfaces in this way.

In some experiments, dropwise condensation was allowed to take place in the presence of a non-condensable gas. In these cases, compressed air or nitrogen was led from its containing bottle into the steam passage without purification or other treatment. The flow of the non-condensable gas was restricted so that its content in steam is of the order of 0.1% by weight, roughly conforming to the allowable air leakage in surface condensers required by B.E.A.M.A. regulations[28]. Fig (3.5) shows the compressed air (or nitrogen) passes, after the reducing valve (A), through a short length of thermometer stem (B) as restriction. The quantity of flow is indicated by the mercury column (C) which has been roughly calibrated. Calibration was done by passing the gas into a bottle (D) of known volume and watching its increase in pressure in relation to time. The amount of steam, which was generated inside the boiler flask only in these tests, was measured by collecting the condensate from the auxiliary condenser. From these, the amount of air content in the entering steam could be roughly estimated.



(a) Front View



(b) Rear View

Plate(3.1) General Arrangement of the Apparatus.

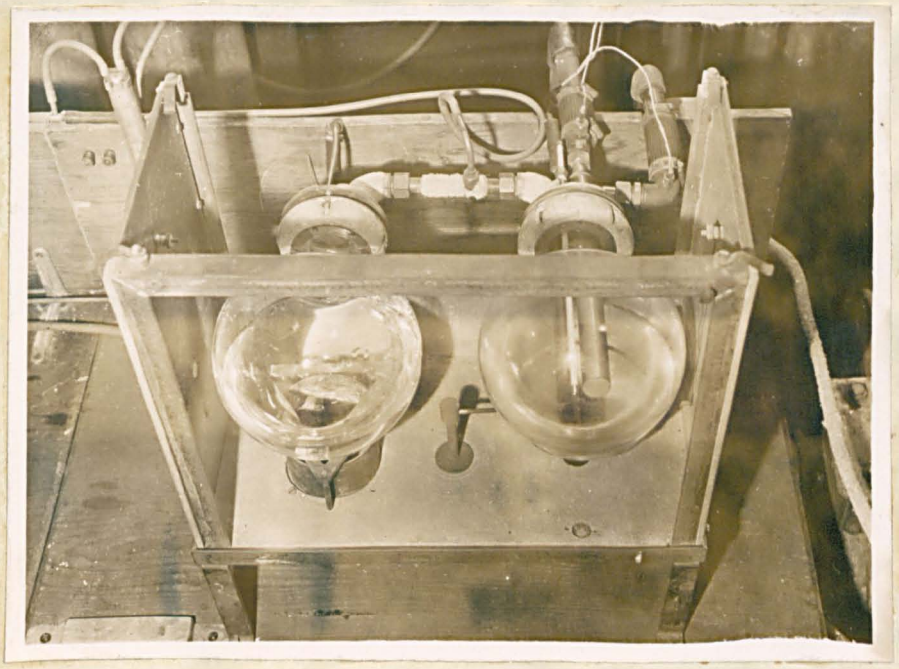


Plate (3.2) Close-up View of One Set (with some covers removed).

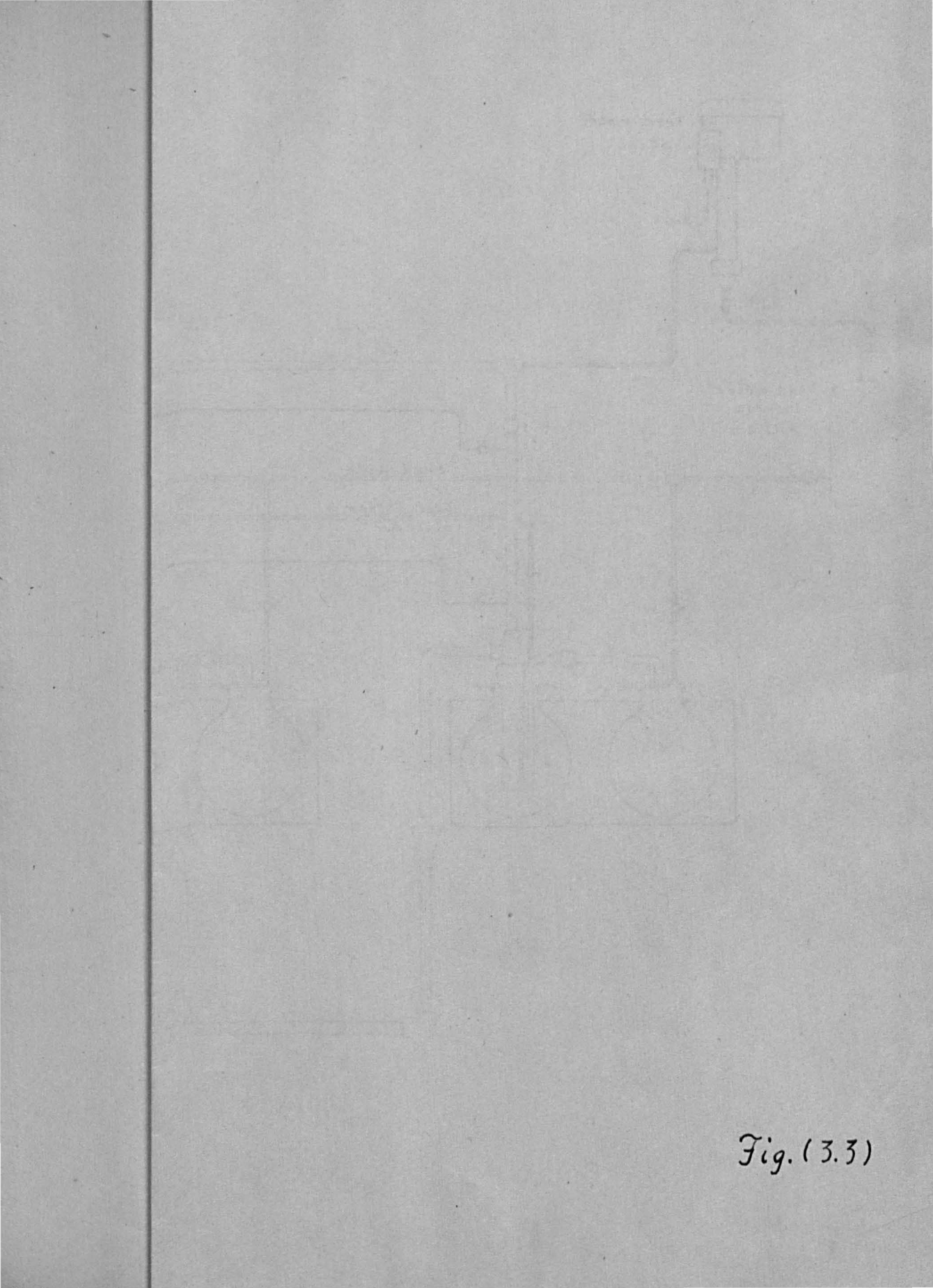


Fig. (3.3)

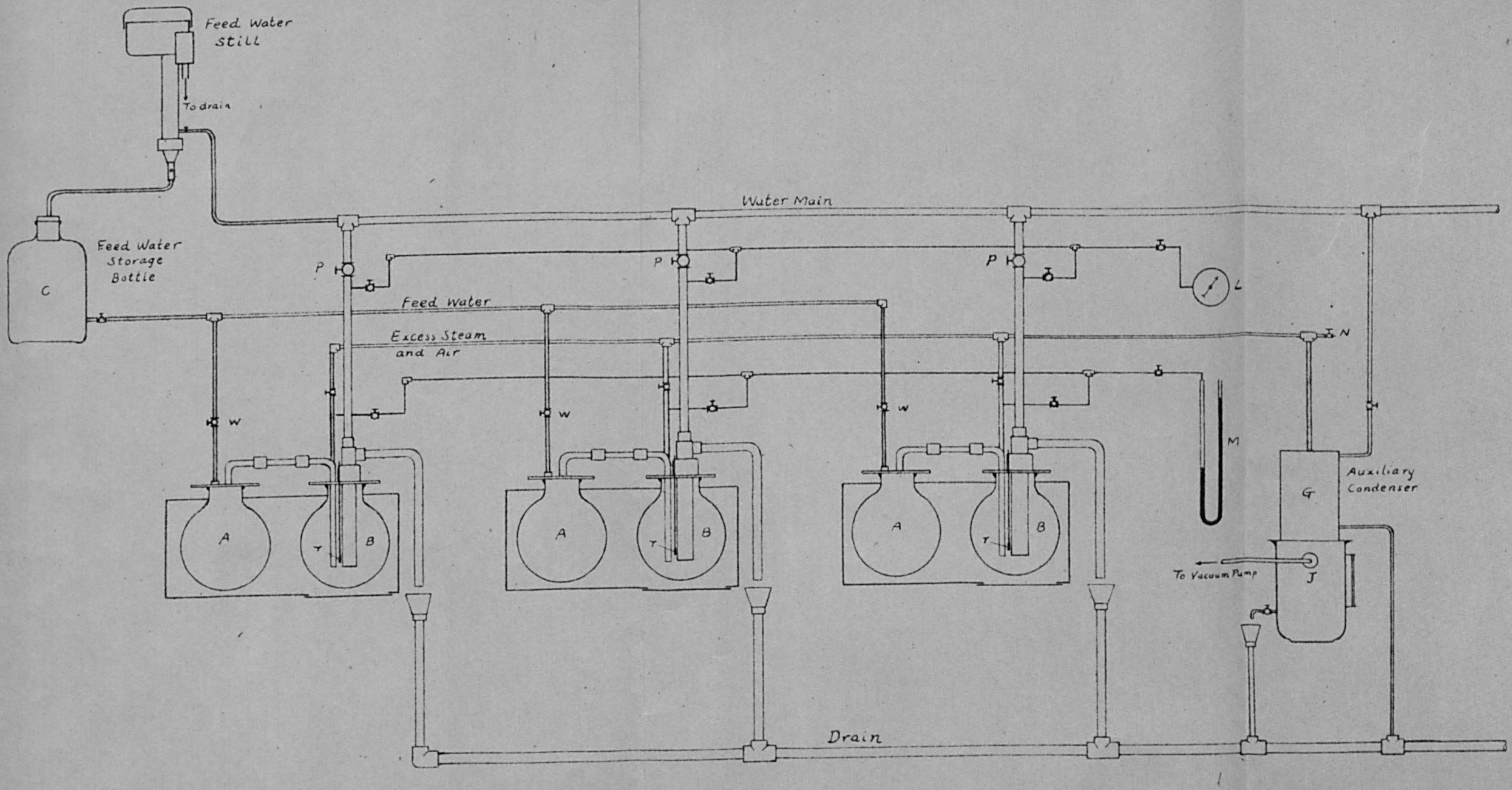


Fig.(3.3). General Arrangement of the Apparatus.

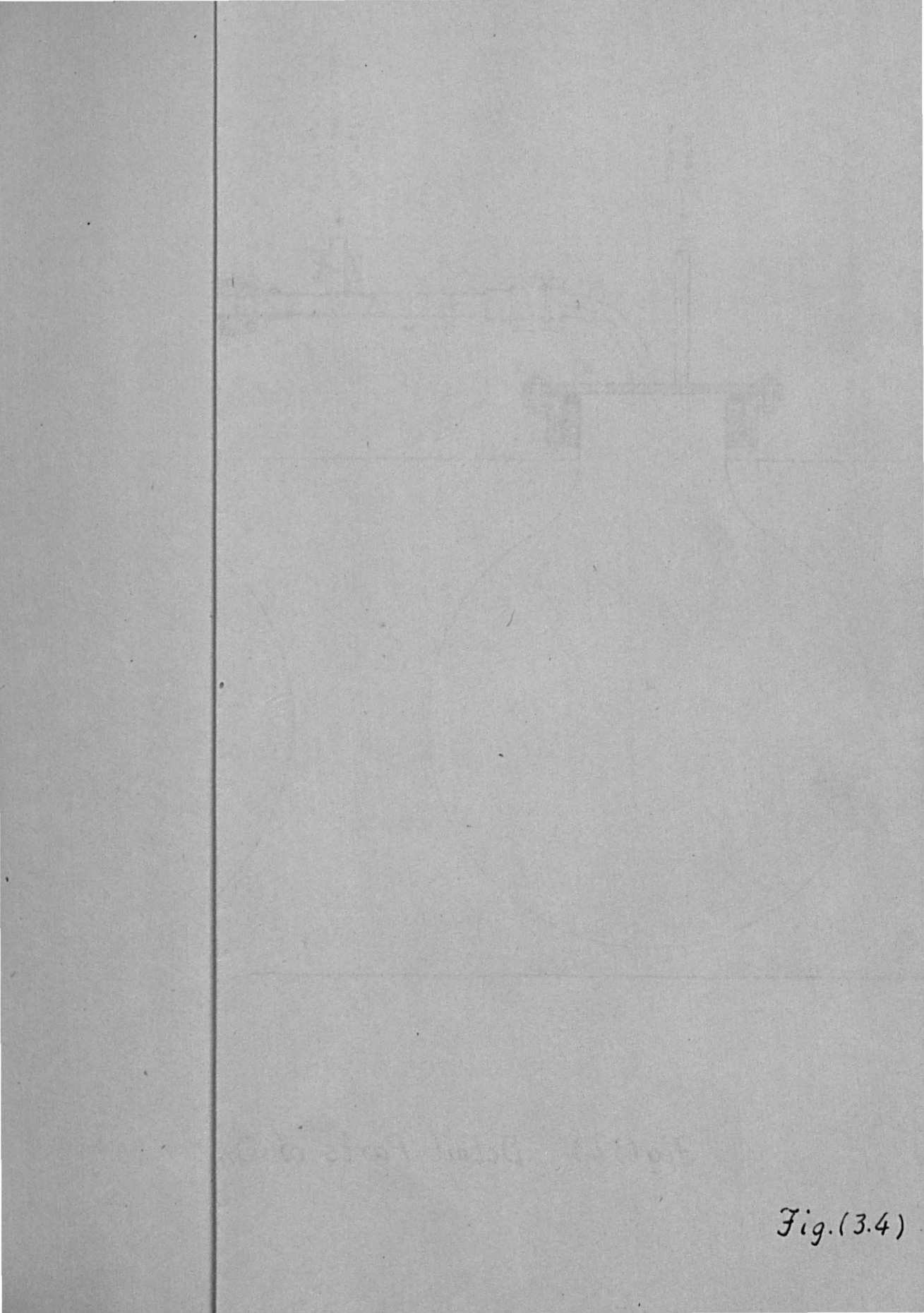


Fig. (3.4)

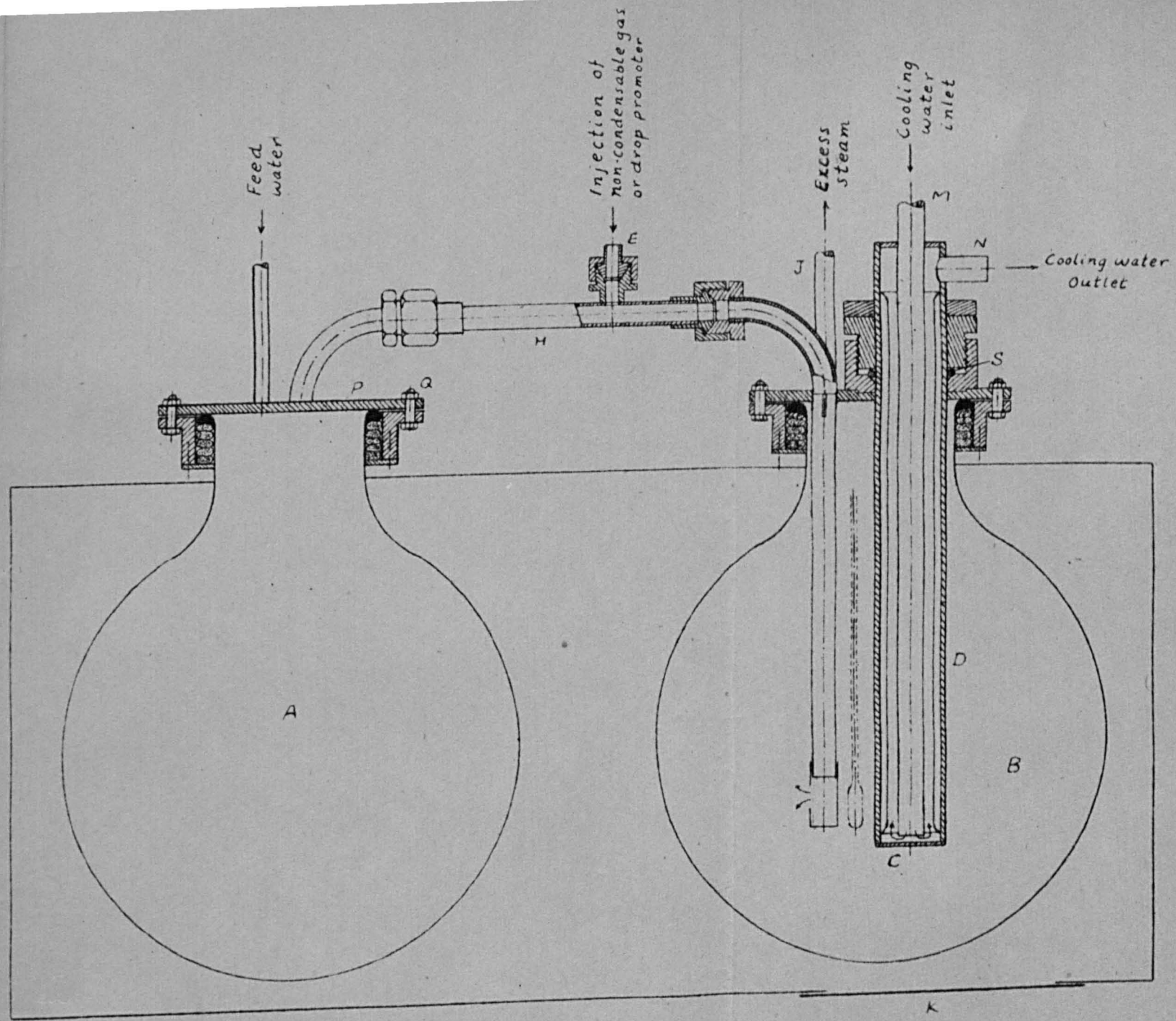


Fig.(3.4) Detail Parts of One Set.

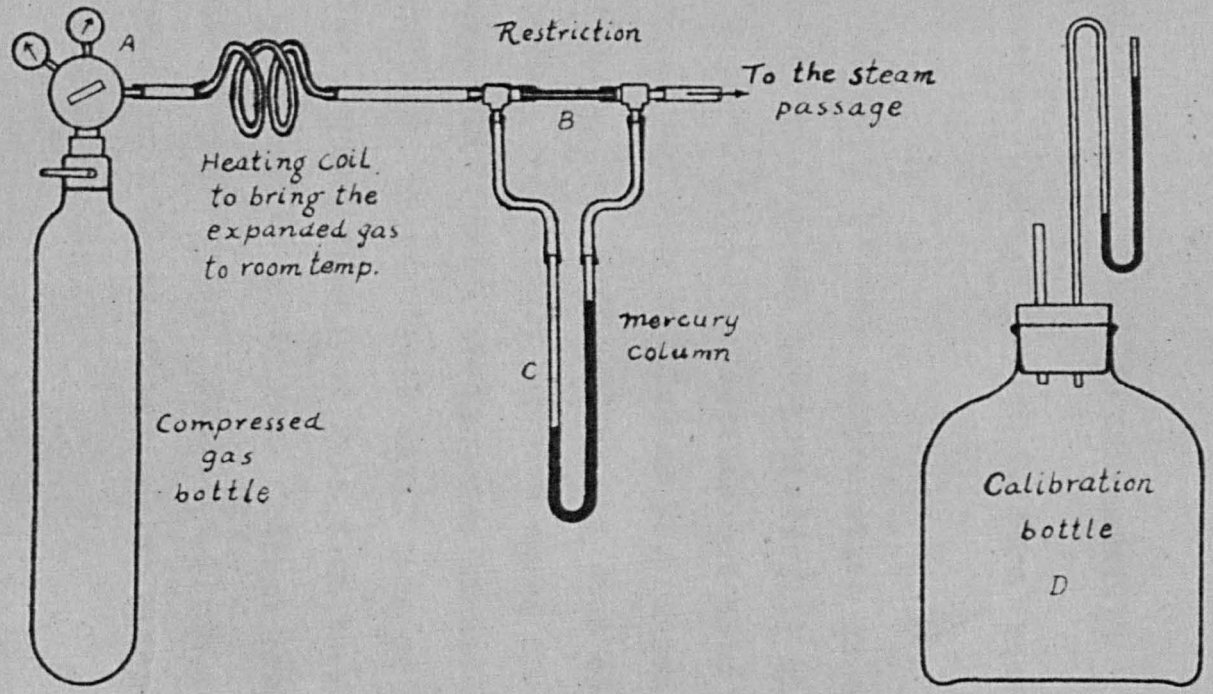


Fig. (3.5) The Injection of Non-condensable Gas.

CHAPTER 4

MECHANISM OF DROPWISE CONDENSATION

--- General Observations and Related Theories.

In the process of dropwise condensation on a vertical surface, parts of the surface are periodically cleared of the covering drops by their coalescence and also by the sweeping action of the down rolling drops. These areas are temporarily left exposed to the steam and soon appear to be covered with minute, apparently uniform sized droplets. Rapid coalescence takes place among these minute droplets to produce bigger and bigger drops until some of them reach a certain limiting size, then roll down the surface, taking in all the drops in their way. Fresh small droplets again originate in their wake. Plate (4.1) shows the general appearance of a vertical surface on which dropwise condensation is taking place.

Droplets grow mainly by coalescence, the growth of droplets by condensation on their surface has lesser significance particularly when the drop size increases. At

first the drops are apparently of uniform size and distribution, but assume a greater variety of sizes as the period of time since the origination of the droplets increases. Even then pictures taken at successive intervals of time of the path previously swept over by a falling drop showed that at any stage there is an outstanding size to which most of the drops belong, and the pitch (or spacing) for drops of this size is roughly twice their diameter, see Fig.(4.5)

When a surface is freshly treated with a suitable drop promoter, the drops appear to be remarkably round and fine grained. As time goes on they become bigger, flatter, and less regular in shape, suggesting a change in contact angle is gradually taking place. Finally the surface deteriorates into mixed condensation. The duration with which a promoted surface maintains dropwise condensation depends on many factors and will be discussed in the next chapter.

Under normal conditions, the drop formation is so quick that it is not possible to follow it with the naked eye aided or unaided or with ordinary speed cine cameras. The question whether the minute droplets originate from condensation around the nuclei supposed to exist on the surface (oxide crystallites) or whether the steam condenses in a thin layer of water film which later contracts into droplets is

only a matter of conjecture. But at a very much reduced rate of condensation (e.g. when the steam supply is cut off and the surface kept cooled so that there is insufficient steam to condense rapidly), some coloured fringes can be barely seen under a white light immediately behind a rolling drop. Some moving picture records of these fringes are shown in Plate (4.2). Similar fringes of still better definition were observed under a monochromatic light (mercury green), but were unable to record on negative films due to insufficient light intensity. These interference fringes indicate the existence of a thin layer of liquid film immediately behind a rolling drop. They also show that the film has a tapered thickness and that the thickness is equal along the curves parallel to the trailing edge of the circular rolling drop at various stages. This thin liquid film was not the tail left by the rolling drop, since when a water drop was allowed to roll down the same surface in the absence of steam, no such interference fringes were observed. Therefore it must be assumed that the water film is due to the condensation of fresh steam on the exposed areas. It may be either that the steam condenses initially as a liquid film or, what would finally appear to be the same thing, that the nuclei are so closely packed that droplets join together as a liquid film as they form. In either case,

the thickness of the film should increase in the direction away from the rolling drop until the film breaks into droplets on reaching a certain unknown maximum thickness. A liquid film on a non-wettable surface must be unstable and tend to contract into droplets when conditions change slightly by thickening of the film. Perhaps there is a certain minimum size for drops to remain separated on the surface, and the film must grow to the thickness giving sufficient condensate to break into this size of drop. As the film contracts into droplets, a certain portion of the area must be again temporarily exposed. A consideration of the balance of surface energy before and after breaking into droplets would indicate that the fractional area again exposed when the unstable film breaks into droplets depends on the contact angle only.

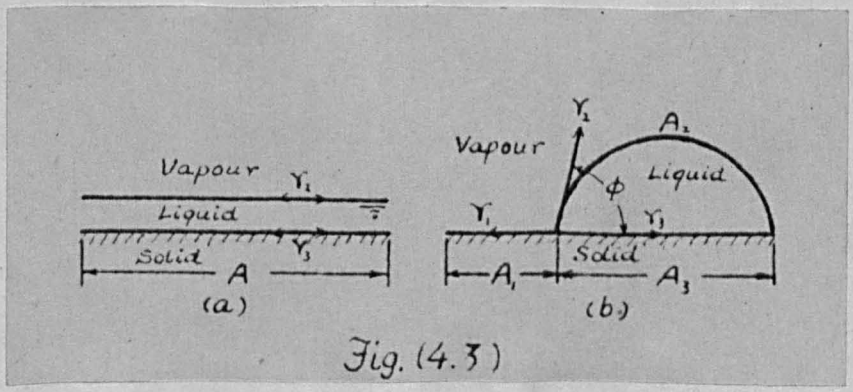


Fig. (4.3)

Fig.(4.3) shows the moment the unstable liquid film (a) breaks into droplets (b). Let A be the total area originally

covered by the film, and let A_1, γ_1 ; A_2, γ_2 ; and A_3, γ_3 be the area and surface tension of different interfaces as indicated by Fig.(4.3). Before breaking into droplets the surface energy is $A(\gamma_2+\gamma_3)$. After breaking into droplets it is $A_1\gamma_1+A_2\gamma_2+A_3\gamma_3$. Assuming the surface energy remains the same before and after breaking into droplets, we have

$$A.(\gamma_2+\gamma_3) = A_1\gamma_1 + A_2\gamma_2 + A_3\gamma_3 . \qquad (4.1)$$

In addition, we have

$$\gamma_1 = \gamma_3 + \gamma_2 \cos\phi , \qquad (4.2)$$

$$A = A_1 + A_3 . \qquad (4.3)$$

From eq.(4.1), (4.2), and (4.3), we have

$$A = A_2 + A_1 \cos\phi . \qquad (4.4)$$

Since the droplets are very small, their surface may be taken as being spherical so that

$$A_2 = \frac{2}{1+\cos\phi} A_3 = \frac{2}{1+\cos\phi} (A - A_1) . \qquad (4.5)$$

From eq. (4.4) and (4.5), we have

$$\frac{A_1}{A} = \frac{1}{2+\cos\phi} , \qquad (4.6)$$

and

$$\frac{A_3}{A} = \frac{1+\cos\phi}{2+\cos\phi} . \qquad (4.7)$$

Assuming that the droplets are evenly spaced, and denoting their pitch and diameter by P and D respectively, we have, referring to Fig.(4.4),

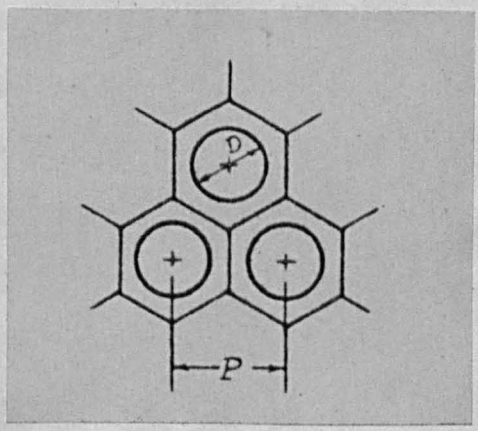


Fig. (4.4)

$$\frac{A_3}{A} = \frac{\text{area of circle}}{\text{area of hexagon}}$$

$$= \frac{\frac{\pi}{4} \cdot D^2}{\frac{\sqrt{3}}{2} \cdot P^2}$$

$$= \frac{\pi}{2\sqrt{3}} \left(\frac{D}{P}\right)^2 . \qquad (4.8)$$

From eqns.(4.7) and (4.8), we have the pitch-diameter ratio

$$\frac{P}{D} = \sqrt{\frac{\pi}{2\sqrt{3}} \cdot \frac{2+\cos\phi}{1+\cos\phi}} = 0.952 \sqrt{\frac{2+\cos\phi}{1+\cos\phi}} . \qquad (4.9)$$

Eqn.(4.9) suggests that the droplets are rather closely arranged, the pitch-diameter ratio being 1.35 when $\phi = 90°$ and 1.23 when $\phi = 60°$,Fig.(4.6). Eqn.(4.6) shows that the fractional area again exposed when the initial film breaks into droplets depends on the contact angle only, being 0.50 when $\phi = 90°$, and 0.40 when $\phi = 60°$, Fig.(4.7) . From these exposed areas liquid film again originates which, owing to the compact arrangement

of the neighbouring droplets, is more likely to be drawn into them rather than contracting into more new droplets. In the meantime the growth of the droplets by condensation on their surfaces may not be negligible when the drops are so small. At any rate the droplets grow and coalescence takes place whenever two droplets happen to touch each other. Here again some area is exposed on coalescence.

Assuming geometrical similarity of different sized drops, a consideration of simple geometry shows that if two drops coalesce, the fraction of the total area originally occupied by two drops which is exposed on coalescence depends on the relative size of the drops, being 0.205 for drops of equal size and 0.133 for two drops of size ratio 2:1, Fig.(4.8).

The limiting size to which a drop grows before it rolls off is significant since with a small limiting drop size, the average size of all the drops on the surface will also be smaller hence a higher heat transfer coefficient is expected. When a brass surface was treated with a mixture of oleic acid and benzyl mercaptan, the drops appeared to be finer grained than for the same surface treated with a mixture of oleic acid and a light lubricating oil. Actual measurement of the steam side coefficients in another apparatus at Queen Mary

College showed a corresponding increase from 25,000 to 30,000 B.t.u. /ft^2 - hr - °F.

When drops are formed hanging from a horizontal surface, it is possible to find out the theoretical shape of the drops and also incidentally their limiting size. Consider the hanging drop in Fig.(4.9) being supported against gravity by its surface tension. From the conditions of equilibrium we have the following equation

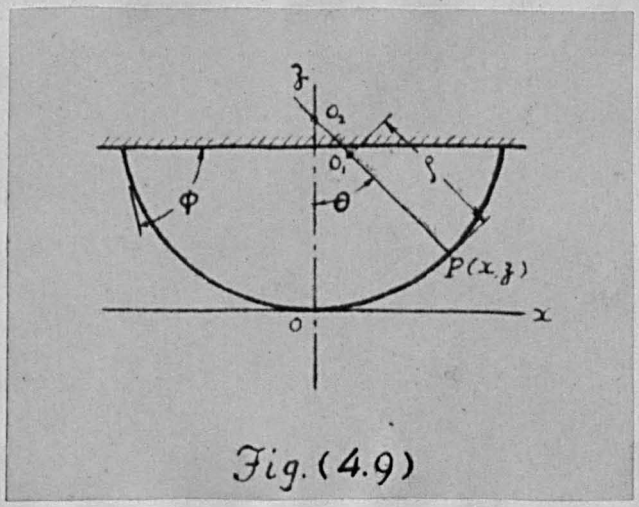


Fig. (4.9)

$$\frac{1}{\frac{\rho}{b}} + \frac{\sin\theta}{\frac{x}{b}} = 2 - \beta \frac{z}{b} \quad . \qquad (4.10)$$

where $\beta = \frac{g \sigma b^2}{T}$,

and ρ = the radius of curvature at any point P,

b = the radius of curvature at o ,

g = the gravitational constant,

σ = the density of the liquid,

T = the surface tension of the liquid.

The exact solution of eq. (4.10) can not be found. However numerical solutions were found already worked out by Bashforth and Adams [3] . The following analysis is based on their numerical results.

Fig.(4.10) shows the successive stages in the formation of a hanging drop which meets its supporting surface at zero contact angle. All the shapes shown in Fig (4.10) are compatible with eq.(4.10) although hanging drops are never seen to assume such shapes as corresponing to β less than 1.0 . The reason can be seen if the volume of its contained liquid is plotted against β ,Fig.(4.11). It shows the volume of liquid increases as β takes successive values 4, 3, 2, ··· , it goes through a maximum volume at $\beta = 1.5$ approximately and then decreases. Hence for the same amount of liquid there are two alternative shapes both of which are compatible with the basic equation (4.10). For instance, when the dimensionless term $V/\left(\frac{T}{\sigma g}\right)^{\frac{3}{2}} = 17.2$, the hanging drop has two

alternative shapes corresponding to β = 1,0 and 3,0. But the shape β = 3,0 is preferred because it possesses less potential energy (surface energy plus gravitional energy) in that configuration.

Fig.(4.12) shows hanging drops having contact angle $\phi = 90°$. Here again the term $V/(\frac{T}{\sigma g})^{\frac{1}{3}}$ has a maximum value at β = 0.57 as shown on the curve, Fig.(4.13).

Values of maximum $V/(\frac{T}{\sigma g})^{\frac{1}{3}}$ were taken for different values of contact angle and plotted in Fig.(4.14) for water and some other liquids. It shows that the maximum volume of a hanging drop decreases with increasing contact angle.

Experiments were made in which a hanging drop was allowed to grow by introducing liquid through a minute hole through the supporting surface and its optical projection recorded on a piece of sensitive paper. Fig.(4.15) shows the diagram of the optical arrangement which is simple and self explanatory. The drop at its maximum size is in an unstable condition; the technique to get its image with the said apparatus involved a suitable adjustment of the intensity of the light source which remained dimmed at first but was suddenly intensified just before the drop

fell off. Plate (4.16) shows the recorded pictures of the maximum hanging drops for contact angle $\phi = 0^\circ$ and 92°. The maximum volume found from these photographs agreed fairly well with the theoretical values as can be seen in the following table :

Contact Angle	Maximum Volume of Hanging Drop	
	Experimental	Theory Indicates*
0°	0.399 c.c.	0.387 c.c.
92°	0.061 c.c.	0.065 c.c.

* Water at 20° C.

Owing to mathematical difficulties, the limiting sizes for drops on planes of other inclinations cannot readily be found. However it would be reasonable to assume that the same tendency is followed, namely, the limiting size decreases with increasing contact angle.

Thus the contact angle seems to play an important part in dropwise condensation. Its measurement is as simple in principle as it is difficult in technique. There are numerous methods of measuring contact angles among which were the following:- (1)

(1) Rotating cylinder method,

(2) Tipping bar method, and

(3) Direct photography.

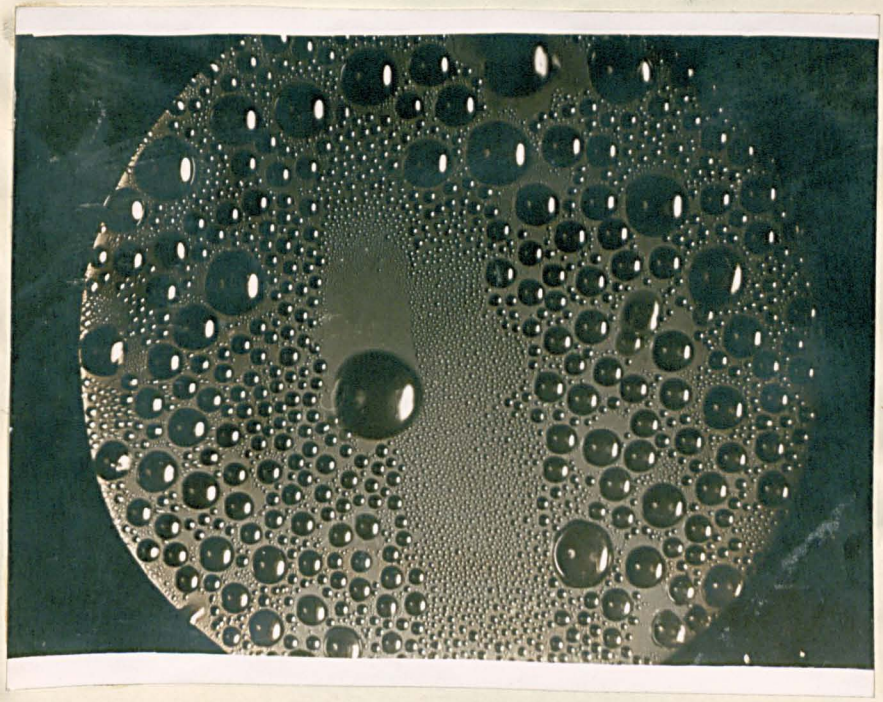
Whatever the method is, their precise measurement requires that all the interfaces be in an ideal, uncontaminated condition. In the case of applying it to dropwise condensation, it is further complicated by the fact that the solid surface is by no means isothermal. In the present investigation, some time has been spent to find the contact angles by simply introducing a drop of water on a treated surface and then viewing its projected shadow at room temperatures in the apparatus shown in Fig.(4.15). Preliminary trials showed that the results were as a whole unrevealing. There appeared to be a gap between their measurement in the above-mentioned manner and the condensation tests. To reproduce the conditions as actually prevailing in condensation tests would require that the treated solid surface be "steamed" to remove the excess promoter before measurements, and that the measurements be taken at elevated temperatures. However this appeared to amount to an undertaking which takes too long a time to accomplish.

Owing to the fact that in dropwise condensation parts of the surface are periodically cleared of their covering drops, local surface temperature is expected to be of a fluctuating nature as indeed shown by Gnam (11) and also

recently by Ozisik in Queen Mary College. Consider that part of the surface which is just cleared of its covering drops and is temporarily exposed to steam. It is a long held view that the rate of condensation of pure steam upon a cooled surface is unlimited. Osborne Reynolds [14], when investigating the condensation of a mixture of air and steam upon a cooled surface, concluded that "there is no limit to the rate at which pure steam will condense upon a cooled surface but the power of the surface to carry off the heat." In other words, to allow for condensation, very little or practically no temperature drop is required between the surface and the steam. Hence the temperature of the local surface which is exposed to steam must be raised up very nearly to the saturation temperature of the steam. However, based on the molecular theory of condensation and evaporation, Silver [17] showed recently that there is a definite temperature drop across the liquid-vapour interface if condensation is to take place. This "interface resistance" is small for steam condensing under atphospheric pressure, but is significant under high vacuum conditions. If this small but definite temperature drop does exist, then the exposed areas will be at a temperature somewhat lower than the saturation temperature of the steam. In any case, this high local surface temperature starts to fall when the condensate builds up an appreciable resistance to heat flow,

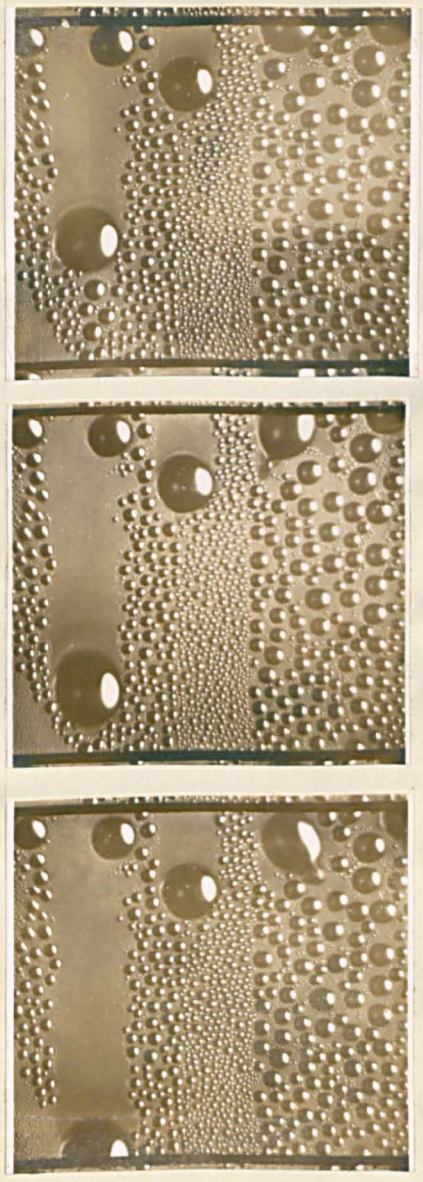
and it continues to fall as its covering drop grows, until the local surface is again exposed.

This surface temperature fluctuation is characteristic of dropwise condensation and, to the present writer's view, should be taken into consideration in analyzing the steam side coefficient. Steam side coefficient would be infinitely big or nearly so had not the cooled surface been partially covered with the condensate drops. Since in dropwise condensation, parts of the cooled surface are obstructed, to various extent, from transmitting heat by their covering drops, so the steam side coefficient, considering the cooled surface as a whole, would turn out to be finite. This is the view held by the present writer and it is based upon this conception that he attempted to make an analysis with the ultimate aim to work out a steam side coefficient as will be described in the later chapters.



Plate(4.1) General Appearence of Dropwise Condensation on a Vertical Surface.

(about 4x magnification)



Plate(4.2) Interference Fringes appeard behind a falling drop when condensation was taking place at reduced rates.

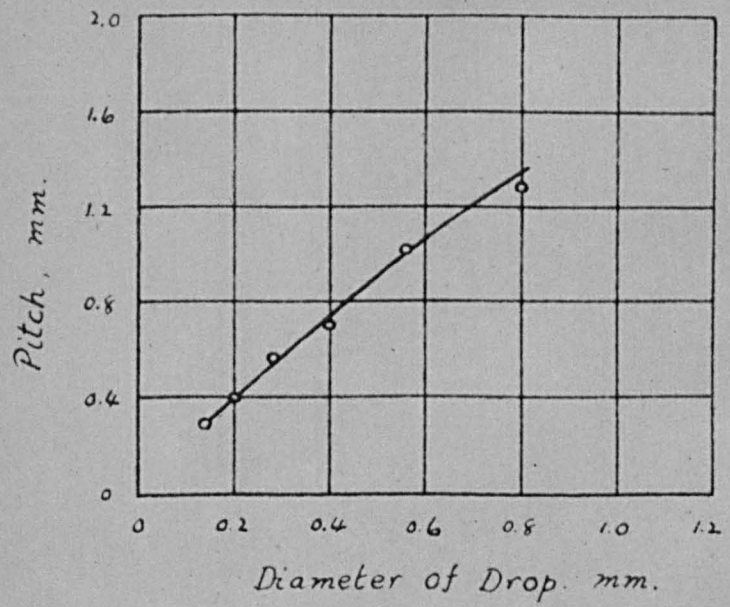


Fig.(4.5). The Spacing of Small Size Drops as Found Experimentally.

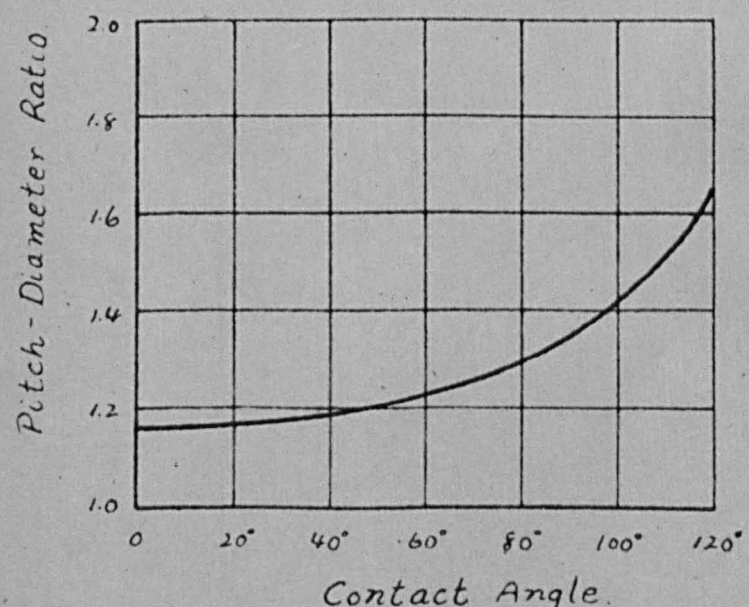


Fig.(4.6). The Spacing of Drops As They First Formed from Liquid Film.

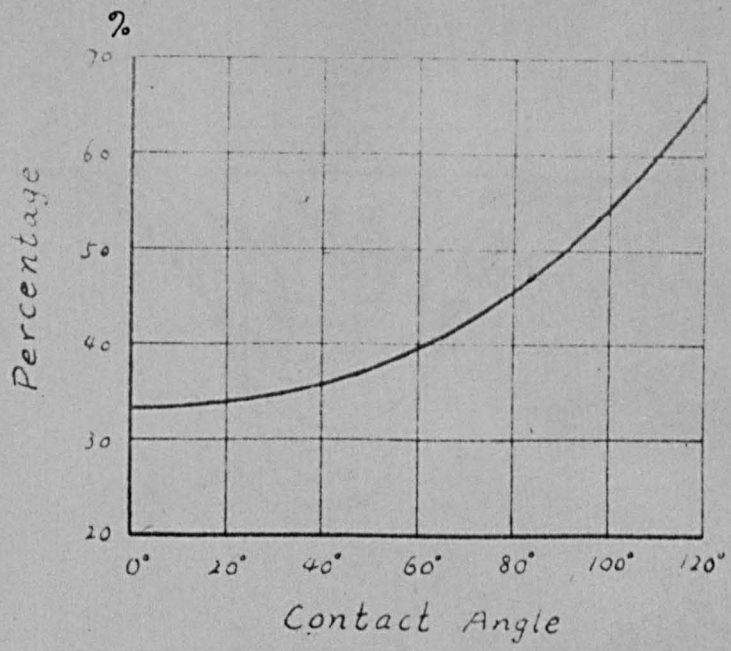


Fig.(4.7) Percentage Area Exposed when an Unstable Liquid Film Breaks into Drops

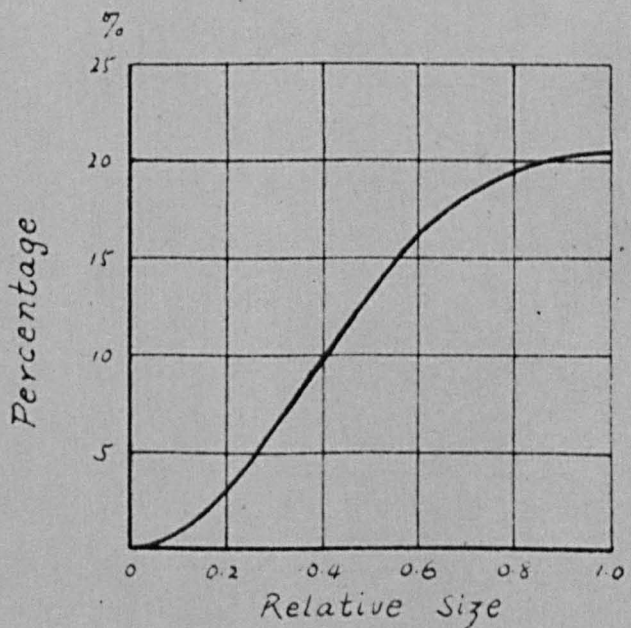


Fig.(4.8) Percentage Area Exposed by the Coalescence of Two Drops

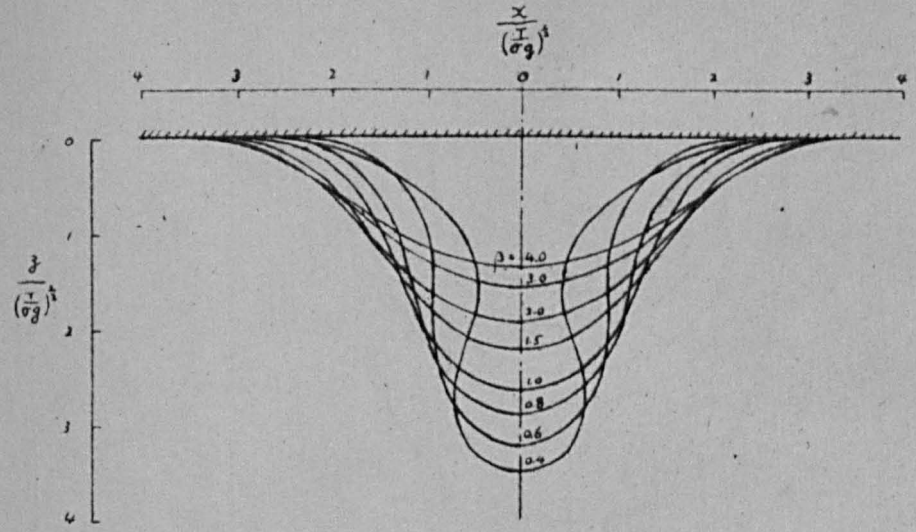


Fig. (4.10)

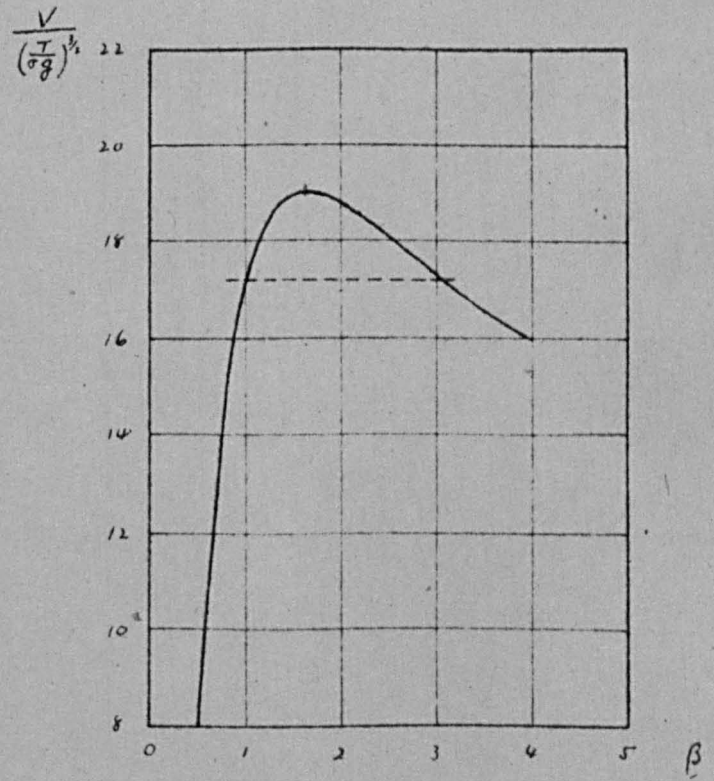


Fig. (4.11)

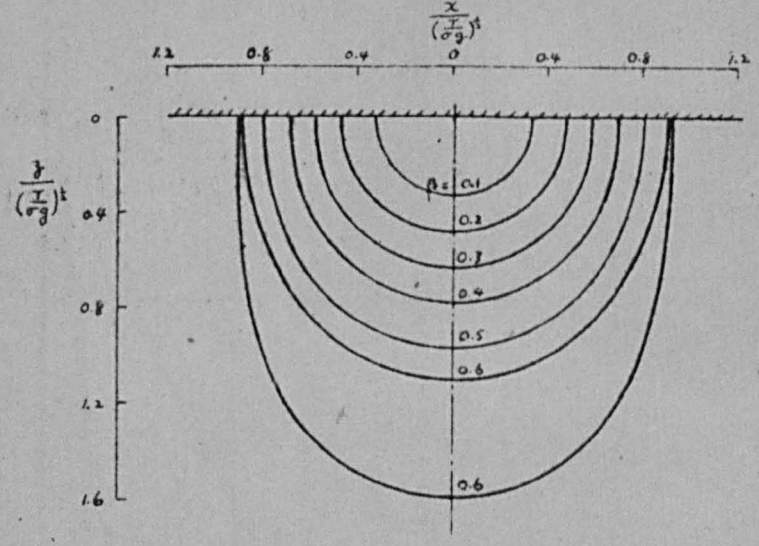


Fig. (4.12)

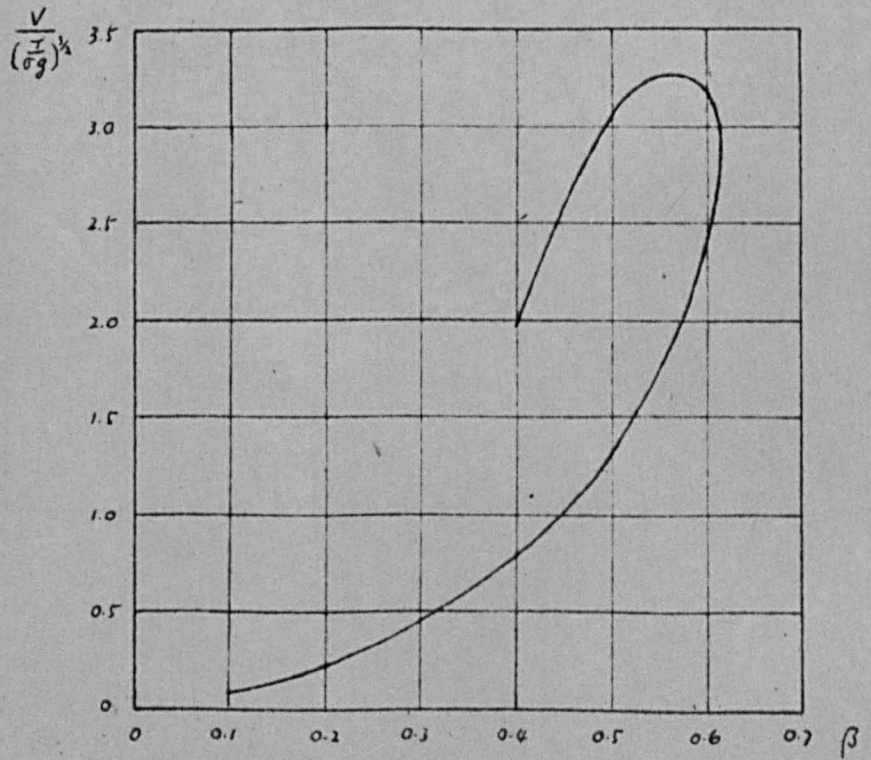


Fig. (4.13)

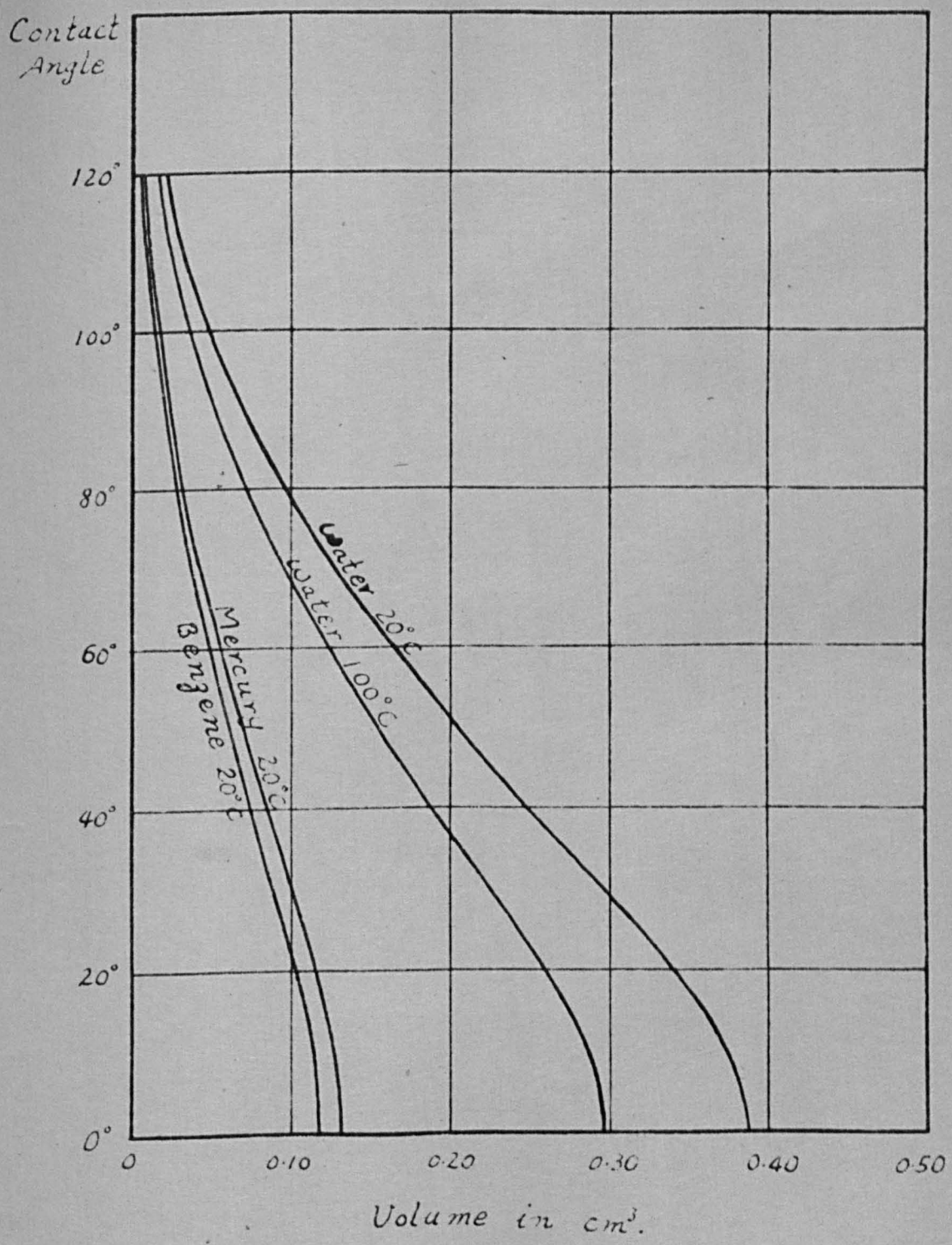


Fig.(4.14). Limiting size of hanging drops

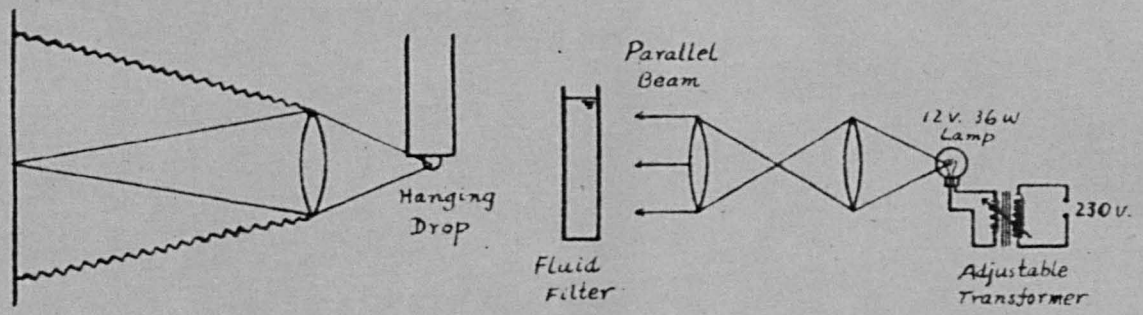


Fig. (4.15) The Optical Arrangement to Check the Maximum Size of Hanging drops Experimentally.

(a) 0° Contact Angle

(b) 92° Contact Angle

Plate (4.16) Pictures of two hanging drops at their maximum size.

CHAPTER 5

BEHAVIOUR OF DROP PROMOTING SURFACES

It has been mentioned previously that the type of condensation depends mainly on the condition of the surface and that in order to get one or other types of condensation, the surface must be suitably treated.

Complete wettability is recognized as a critical test of a clean surface in electroplating plants. Brass and copper surfaces can be easily cleaned or, in other words, made wettable by rubbing them with flour emery powder or finely powdered metal magnesium on a piece of wet felt. Highly polished stainless steel and chromium plated surfaces hold a contaminant film more firmly; they can be made completely wettable after repeated rubbing with flour emery powder on wetted felt. Care must be taken to distinguish between a real wettable and therefore clean surface and a surface which may still have patches of greasy film but shows apparent wettability if flooded with water. In the latter case, non-wettable parts show themselves when water is wiped off. Even a highly polished chromium plated surface, if it was properly cleaned, would not lose its complete wettability after hours' standing dry in the atmosphere.

With steam generated from distilled water inside a reasonably clean vessel, complete filmwise condensation was invariably observed on a clean surface, this confirmed the findings of Drew, Nagle, and Smith[7] . Complete filmwise condensation could be maintained for 5 to 6 hours when the present apparatus had been cleaned in the manner described on P. 31 , Chapter 3 . After the apparatus had been in continual use, in filmwise runs, for 2 or 3 days, complete filmwise condensation was maintained from beginning to end throughout 24 hours' run on a highly polished stainless steel surface. This shows the degree of cleanliness which the present apparatus could be relied upon and was considered as satisfactory.

Dropwise condensation is procured by coating the metal surface with a suitable drop promoter. To compare the effect of various factors on the stability of drop promoting surfaces, care was taken to prepare the surfaces in identical manner as far as possible. The surface treatment was as follows:

(1) Polished to the desired surface finish.

(2) Washed with carbon tetrachloride or trichloroethylene to remove as much as possible any greasy matter.

(3) Rubbed with powdered metal magnesium or flour emery powder on wetted felt until the surface was completely

wettable, then rinsed under tap water and wiped with the same wetted felt after which any water left on the surface soon evaporates away.

(4) Drop promoter (which is generally a liquid) was applied to the surface with a corner of clean filter paper. Too much promoter is not desirable and was always wiped off so that only a uniform, thin layer is left on the surface.

To polish the metal surface to the desired surface finish, the usual procedure of metallurgical specimen polishing was followed. Polishing was started with a suitable grade of emery paper in a single direction till all the scratches in other directions disappeared. Then changed into the next finer grade emery paper, polishing again in a single direction perpendicular to the previous polishing operation until all the scratches left by the previous polishing disappeared. This was followed up until the desired grade emery paper had been used. The final scratches were invariably in vertical directions when the surface was in its working position. Brass surfaces can be easily polished dry to the finest grade emery paper. In polishing copper and stainless steel surfaces, liquid paraffin was used as a lubricant. The available grades of emery paper were,

in the order of increasing smoothness, Nos. 3, 2, 1, 0, 00, 000, and 0000. In experiments to examine the effect of surface finish, the surfaces were finally polished with No. 3, 0, and 0000 emery paper respectively and the results were compared. As judged by common sense, they should cover the range of commercial surface finish of rolled or cold drawn products.

Surfaces of mirror finish were polished on the faceplate of 6" diameter polishing heads rotating at 1500 r.p.m. The face-plate of one polishing head was lined with soft felt; that of another was lined with chamois leather. The metal surface was first polished on felt with alumina powder suspended in water as the dressing. Then changed to chamois leather dressed with rouge and liquid paraffin. A surface after this polishing reflected light like a mirror, but was seen to be a matt surface when carefully examined. A polishing operation like this is expected to produce a Beilby layer surface (4) compared with the abraded surface resulting from polishing with emery papers.

The test surface, after being prepared in the above manner, was inserted into the condensing chamber flask; the cooling water being turned on before steam was generated.

In the earliest stage, the steam meets the cooled surface and forms big and irregular shaped drops or even rivulets if an excessive amount of promoter is on the surface. When there was too much promoter, a thick jel formed which takes a long time to be washed off. That is why after applying the drop promoter, the surface was always wiped so that only a thin layer of promoter was left on it. If this is done, excessive promoter will be washed off within 5 to 10 minutes, after which dropwise condensation appears.

The drops are remarkably round and fine grained in the beginning, but gradually become bigger. This is especially so for brass and copper surfaces treated with oleic acid in which case the change in appearance is apparent with in ½ hour. Stainless steel and chromium plated surfaces are steadier; no appreciable change takes place in the first few hours. As time goes on, the drops become still bigger, flatter, and gradually less regular in shape. In later stages, streaky tails will be left behind when drops roll down. Finally permanent rivulets and film patches appear over much of the surface. At this stage the surface is considered as breaking down into mixed condensation. However, in the case of stainless steel and chromium plated surfaces, drops deteriorate into rivulets locally, often only in one or two places while the rest of the surface

still keeps good dropwise condensation. This condition may go on for a very long time without showing a general breaking down. Therefore for these surfaces the first appearance of a rivulet amid drops was taken as the sign of breaking down. It should be appreciated that in either case the breaking down of dropwise condensation takes place gradually. It is difficult to state precisely when it happened. Periodically photographic records of the progress of the surfaces were therefore necessary. By comparing these photographic records and also, to some extent, using the writer's own judgement, it is possible to assign a duration of time for which the surface can be described as maintaining dropwise condensation. For simplicity, this duration will be referred to as the "life" of a drop promoting surface.

Plate (5.1) shows the photographic record of the progress of a brass surface treated with oleic acid: -
(a) Before excess oleic acid was washed off, drops were big and irregular shaped; (b) Dropwise condensation first appeared after excess oleic acid was washed off, drops were remarkably round and fine grained; (c), (d), ... Successive pictures were taken $\frac{1}{2}$ hr, 1 hr, ... after the first appearance of dropwise condensation, drops were becoming bigger and less regular in shape (g) Streaky tails left

behind when drops rolled off: and (h) The surface was mainly covered with film patches. The life of this surface was given as 2-2½ hrs.

Plate (5.2) shows the progress of a stainless steel surface treated with a mixture of oleic acid and a light lubricating oil. (a) shows 1 hr. after the first appearance of dropwise condensation, and so on. In (c) it tended to be streaky in one place, and in (d) there was a definite rivulet amid drops. The life of this surface was taken as 24-36 hrs.

In the experiments to examine the life of a drop promoting surface as described above, the surfaces were coated with drop promoter only once at the start. Afterwards unpromoted steam was allowed to condense on them throughout the test. No quantitative measurement of the amount of drop promoter was attempted. However, repeated experiments showed reasonably consistent results; the life of a promoted surface was apparently not altered by the amount of drop promoter coated on the surface in the first place. It appeared either that the amount of the promoter left on the surface when dropwise condensation first appeared was more or less constant or that the life of a promoted surface is not directly linked with the thickness of the promoter layer.

So far as the present writer is aware, similar investigation of the life of a drop promoting surface in a manner comparable with the present experiments had not been reported by any previous investigator. Therefore in the earlier stages of the present investigation, the writer had no idea of how long the life of a promoted surface would be. Neither was he sure whether all the important factors had been taken into consideration. For instance, the life of a brass surface treated with oleic acid (a few hours) appeared to the writer as being surprisingly short, and it was suspected whether there was any fault in the surface treatment or the experimental conditions. It was only after repeated experiments that the writer felt confident that it was that given, and regarded the results as established for the time being until they can be confirmed or modified by future investigators.

It will be recalled that Drew et al classified certain promoters as "very effective" if it produced dropwise condensation which lasted over 24 hours (p. 17). The present brass-oleic acid combination comes into this catagory and, according to their experiments, should last over 24 hours as against a few hours found in the present investigation. The deviation is attributable to two reasons:-

(1) The quality of steam is different. In their experiments boiler steam was sometimes used (and was not specifically described for each case) which was known to contain contaminants. Further difference would be caused if it contained air.

(2) If the promoter is injected into the steam chamber (as it was in their experiments sometimes), the condition is not comparable with direct application as it was in the present experiments.

Before discussing the separate effect of various factors upon the life of drop promoting surfaces in detail, some closely associated experiments and observations concerning the behaviour of drop promoting surfaces will be described in the following paragraphs as they may be of interest to other investigators in this field.

Nagle and Drew [٢١] stated that dropwise condensation could not be induced on very rough surfaces. Unfortunately it was not described how rough the surfaces they referred to were. The present writer found that surfaces roughened with the coarsest emery paper he could find still give dropwise condensation just as does a smoother surface, other conditions being the same. This was so even when a copper surface was badly roughened with a wood rasp. On this surface the

formation of the drops was more or less affected by the deep ridges and furrows, but that the type of condensation was dropwise could not be mistaken.

Brass and copper surfaces always became partially wettable after the apparatus had been shut down for several minutes, although they gave complete dropwise condensation prior to shutdown. This was so whether they had been promoted with oleic acid or benzyl mercaptan. On starting again with the same surface undisturbed, the type of condensation was mixed at first, but would gradually turn into dropwise condensation. The turn-over was often complete within a few minutes. A similar effect could not be observed on stainless steel or chromium plated surfaces. This strange behaviour of brass and copper surfaces was also observed by Nagle and Drew [11]. They found when condensation was restarted on their brass tube after a period of shutdown, the overall coefficient increased with time which was later traced to be due to the gradual development of dropwise condensation. They suspected that the change from mixed condensation to dropwise condensation was due to some fresh contaminant being brought on to the surface with the steam. In the present writer's view, that could not be the sole reason, since with the present apparatus there was little possibility of any contaminant being carried in with the steam

especially in sufficient quantity to cause a change into dropwise condensation within a few minutes. For the change from a non-wettable surface to a partially wettable surface occasioned by shutdown, the present writer can see no other explanation apart from the change in surface temperature. But one thing seemed definite: that the promoter layer was on the surface all the time, otherwise how had it disappeared suddenly from the surface? The subsequent rapid development of dropwise condensation on starting again is believed to be stimulated by the presence of air which rushed into the apparatus when the apparatus was shut down, as the presence of non-condensable gas was later found to be outstandingly favourable to dropwise condensation. It was also observed that a promoted surface which had nearly deteriorated into mixed condensation after prolonged hours' condensation could regain its drop promoting power if a small amount of air was injected into the entering steam, other conditions being kept undisturbed. The continuous injection of approximately 0.1% air (by weight) into the entering steam increased the life of a brass surface from 2-2½ hrs. to over 12 hrs. as will be described later.

The injection of certain solvent, such as carbon tetrachloride or trichloroethylene, into the entering steam

caused an interesting change in the appearance of drop formation on a promoted surface. Immediately after its injection, the entire surface appeared to be covered with extremely small droplets rolling off the surface at such a rate that it was impossible to follow by eye. This lasted not more than a few seconds then it died down and the surface resumed its original state. Plate (5.3) shows the appearance of the surface before and shortly after the injection of trichloroethylene. The normal boiling point of trichloroethylene (87°C) and that of carbon tetrachloride (77°C) are well below the probable temperature of the condensing surface. Therefore they must be left as a vapour in the vicinity of the condensing surface after the steam has been condensed. The vast decrease in maximum drop size seems to suggest a corresponding radical change in certain interfacial tensions due to the presence of such vapour.

From the practical point of view, it is desired to find a surface treatment which keeps persistent dropwise condensation all the time. So far attempts towards this direction have not been completely successful. With unpromoted steam, a metal surface initially coated with a drop promoter breaks into mixed condensation sooner or later. This included the coating of a metal surface with silicone varnish which has a

water repellent property:- A brass surface was cleaned with dilute chromic acid and after being dried in an oven, a layer of silicone varnish (diluted in equal portions by volume in solvent naphthalene) was applied and baked for 2 hours at 150°C. With steam at 100°C, a silicone varnished surface gave perfect dropwise condensation initially, but broke down after one hour or so when the varnish film started to peel off. It seems, however, further research in the direction of depositing a thin, permanent, water repellent film on a metal surface stands a good chance of success.

On the other hand, the use of the usual drop promoters is not successful in maintaining dropwise condensation permanently unless the incoming steam also is promoted. Dropwise condensation has been maintained for a comparatively long period of time by injecting drop promoter into the steam. A pad of absorbent cotton wool was pushed through the port (E), Fig.(3.4), so that it projected into the stream of steam. A drop or two of diluted oleic acid (1 part concentrated oleic acid diluted in 4 parts by volume absolute alcohol) were injected every one or two hours into the cotton wool pad by means of a hypodermic needle. This maintained dropwise condensation on a brass surface intermittently throughout 4 days at the end of which the surface looked very dark but gave perfectly round drops.

While no initial treatment of a metal surface with a drop promoter maintained dropwise condensation indefinitely, some surfaces show definitely longer life than others. Among the variables examined in relation to the life of drop promoting surfaces were:

(1) The surface finish;

(2) The rate of heat transmission;

(3) The material of the surface;

(4) The drop promoter; and

(5) The presence of non-condensable gas.

Most of the present work was done with saturated steam at atmospheric pressure. However, a few runs were made under partial vacuum conditions (vacua up to 24 inches mercury). There appeared to be no marked differences in the appearance of drop formation between atmospheric tests and vacuum tests. The air was feared present in the steam chamber in the vacuum runs, as the apparatus was not leak proof. Further investigation of the life of the surfaces under partial vacuum conditions were not continued in view of the inseparable effect of air.

In the following sections the results are presented in a tabular form. As far as possible, most of those tests which could be finished within a day's time were repeated twice, while some of them were repeated many times. Check runs were

made with surfaces of "established" life whenever any doubt regarding the cleanliness of the apparatus was raised. Precise reproducibility is difficult in experiments such as these, but on the whole the results were consistent. All but a few of those tests which took too long a time were not repeated. The results given for them were those of single experiments. However, from them, the general trend of the effect of various factors could not be mistaken.

(1) The effect of surface finish.

In literature, the degree of surface finish often entered into consideration in discussing dropwise condensation. Drew, Nagle, and Smith [7] stated that dropwise condensation can be induced and maintained more easily on highly polished surfaces than on rough surfaces. It was therefore expected that the degree of surface finish might have a significant effect on the life of a promoted surface. This seemed to be a reasonable assumption especially if it were considered that drop formation was closely associated with condensation around the nuclei provided by the surface. However in the present investigation, repeated experiments made on brass surfaces treated with oleic acid showed something not quite expected. A brass surface polished with different grades of emery paper, from No.3. to No.0000, was found to make little difference to its life, except when it was polished to a mirror finish in which case its life is definitely longer. The following table summarizes the results.

Table (5.1) The life of a brass surface promoted with oleic acid.

Steam: Saturated steam at atmospheric pressure

Surface finish		Rate of cooling on the water side		
		low, 1 ft/Sec.	medium, 4 ft/sec.	high, 16 ft/sec.
Rough	No. 3 Emery paper	$3\frac{1}{2}$-4 hrs.	2 - $2\frac{1}{2}$ hrs.	$\frac{3}{4}$ - 1 hr.
Medium	No. 0 Emery paper	3 -$3\frac{1}{2}$ hrs.	2- $2\frac{1}{2}$ hrs.	1 - $1\frac{1}{2}$ hrs.
Fine	No. 0000 Emery paper	$3\frac{1}{2}$ - 4 hrs.	2- $2\frac{1}{2}$ hrs.	1 - $1\frac{1}{2}$ hrs.
Mirror finish	Polished with rouge	12-15 hrs.	8-10 hrs.	4 - 6 hrs.

It appears that the difference exists not so much among various degrees of roughness of the surface as between different types of surface. For a medium rate of cooling on the water side, an abraded surface maintained dropwise condensation 2-$2\frac{1}{2}$ hrs. compared with 8-10 hrs. for a Beilby layer surface.

The results for a stainless steel surface promoted with a mixture of oleic acid and a light lubricating oil are more puzzling. A Beilby layer surface showed a longer life than a fine or medium rough abraded surface, althrough to a lesser extent than brass. But a rough abraded surface gave the longest life of all, as can be seen in the following table.

Table (5.2) The life of a stainless steel surface promoted with a mixture of oleic acid and a light lubricant oil.

Steam: Saturated steam at atmospheric pressure

Rate of cooling on the water side: Medium, 4ft/sec.

Surface finish		Life of surface
Rough	No.3 Emery paper	60-80 hrs.
Medium	No.0 Emery paper	24-36 hrs.
Fine	No.0000 Emery paper	24-36 hrs.
Mirror finish	Polished with rouge	40-60 hrs.

(2) The effect of heat transmission rate.

Table (5.1) shows also quite definitely that other conditions being the same, a drop promoting surface maintains dropwise condensation longer at smaller rates of heat transmission. This is expected since a higher heat transmission rate must be accompanied by a more frequent washing of the surface by the drops of condensate and therefore the surface loses its drop promoting power more rapidly.

(3,4) The effect of the metal of the surface and the drop promoter.

Stainless steel and chromium plated surfaces kept their brightness from start to finish while copper and brass surfaces as a rule showed discolouration after a few hours' run. In the former case, dropwise condensation lasted 1-3 days while in the latter case it seldom lasted more than 10 hours. For the same metal surface, the drop promoter employed also made a difference. For the same rate of cooling on the water side, the life of a brass surface promoted with oleic acid was 2-2½ hours compared with 8-10 hrs. when the same surface was promoted with benzyl mercaptan. The following Table (5.3) summarises the comparison between some different combinations of the metal and the promoter.

Table (5.3) Comparison between some combinations of the metal of the surface and the drop promoter.

Steam: Saturated steam at atmospheric pressure

Surface finish: No.0 emery paper, except chromium plated surface which was mirror finish.

Rate of cooling on the water side: Medium, 4ft/sec.

Metal of surface	Drop promoter	Life of surface
Brass	Oleic acid	2-2½ hrs.
Brass	Oleic acid and a light lubricating oil mixed	2½-3 hrs.
Brass	Benzyl mercaptan	8-10 hrs.
Brass	Benzyl mercaptan and oleic acid mixed	16-24 hrs.
Copper	Oleic acid	2-2½ hrs.
Stainless Steel	oleic acid and a light lubricating oil mixed	24-36 hrs.
Chromium plated	Oleic acid and a light lubricating oil mixed	40-60 hrs.

(5) The effect of non-condensable gas.

It is well known that the presence of a small amount of non-condensable gas in the steam reduces considerably the steam side coefficient and, to a lesser extent, the rate of heat transmission. But the part it plays in maintaining dropwise condensation is not generally appreciated. In the course of the present investigation, various observations pointed to the conclusion that the presence of a non-condensable gas has an important bearing on the life of a drop promoting surface. As has already been mentioned before, when approximately 0.1% air (by weight) was continuously injected into the entering steam, the life of a brass surface promoted with oleic acid was increased from 2-2½ hrs. to 12-24 hrs, the rate of cooling on the water side being kept the same. The continuous injection of 0.1% nitrogen was still more effective. It maintained the same surface in perfect dropwise condensation from beginning to end throughout 7 days and was likely to go on still longer. Although the rate of heat transmission was reduced by the presence of a gas, it tended to make dropwise condensation last longer, the difference in the life of the surface was so big that its effect could not be attributed solely to the reduction of the heat transmission rate. The difference between air

(oxidizing) and nitrogen (non-oxidizing) was also apparent. When 0.1% air was present, a promoted brass surface always showed obvious discolouration within 10-20 minutes' time. When approximately the same amount of nitrogen was present, discolouration of the same surface under otherwise identical conditions was very much retarded; it was only faintly visible after 24 hours' run.

Table (5.4) The effect of non-condensable gas.

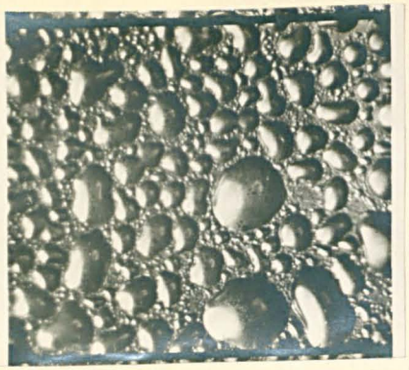
Steam: Saturated steam at atmospheric pressure

Surface finish: No.0 emery paper, except chromium plated surface which was mirror finish

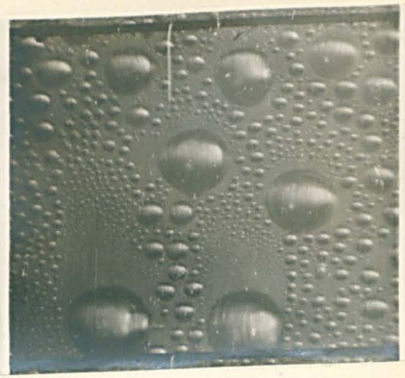
Rate of cooling on the water side: 4 ft/sec.

Metal of surface	Drop promoter	Life of surface		
		Continuous injection of a non-condensable gas		Practically air free steam
Brass	Oleic acid	0.1% air	12-24 hrs.	2-2½ hrs.
Brass	Oleic acid and a light lubricating oil mixed	0.1% air	12-24 hrs.	2½-3 hrs.
Brass	Benzyl mercaptan	0.1% air	24-36 hrs.	8-10 hrs.
Brass	Oleic acid	0.1% N_2	From beginning to end throughout 7 days.	2-2½ hrs.
Chromium plated copper	Oleic acid and a light lubricating oil mixed	0.1% air	From beginning to end throughout 7 days.	40-60 hrs.

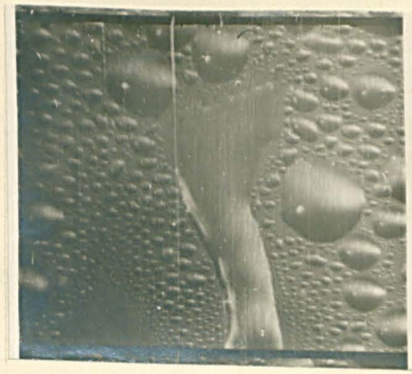
Plate (5.1)



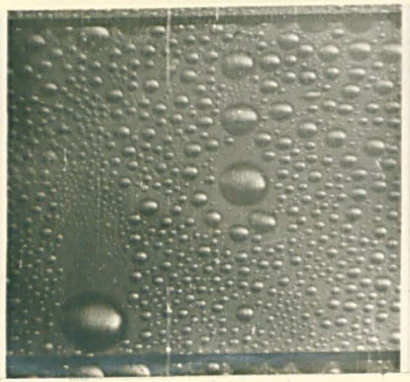
(a) Before excess oleic acid was washed off.



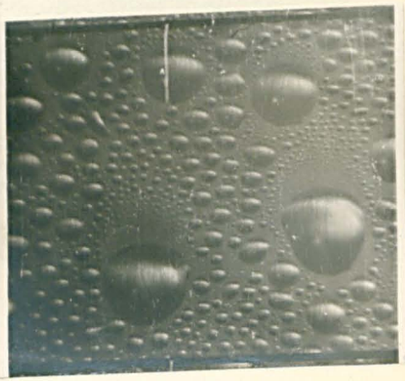
(d) 1 hr.



(g) $2\frac{1}{2}$ hr.

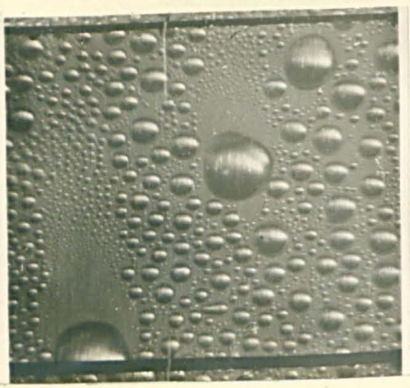


(b) Dropwise condensation first appeared.

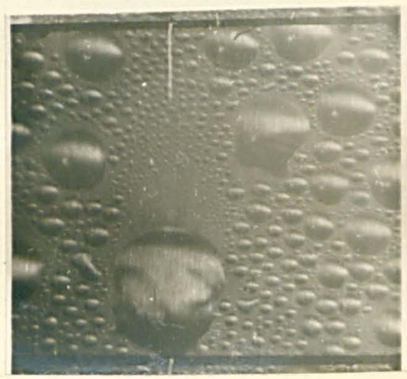


(e) $1\frac{1}{2}$ hr.

(h) 3 hr.



(c) $\frac{1}{2}$ hr. later.

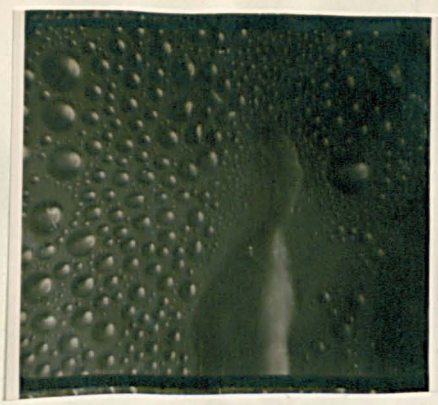


(f) 2 hr.

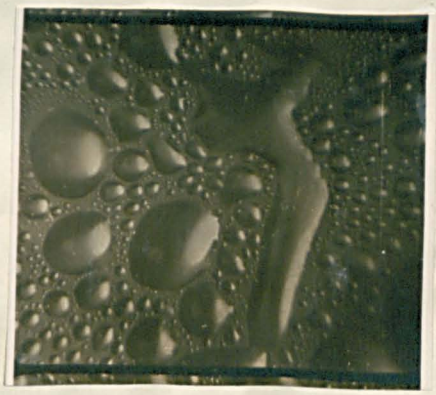
Plate (5.1) Progress of a Brass surface treated with oleid acid.

(a) 1 hr.

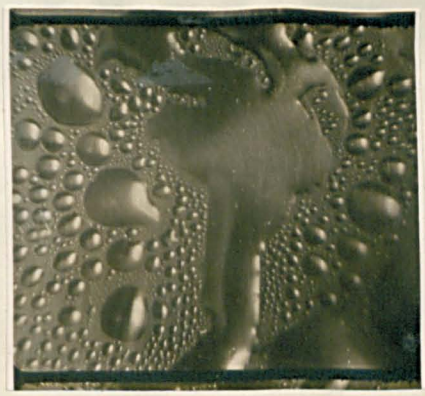
(b) 12 hrs.



(c) 24 hrs.

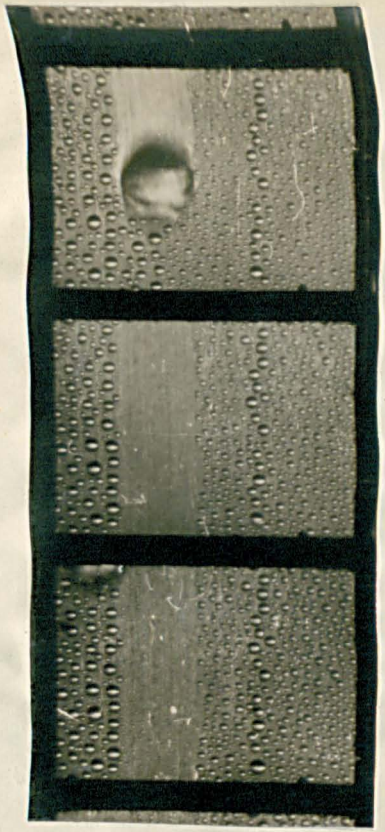


(d) 36 hrs.

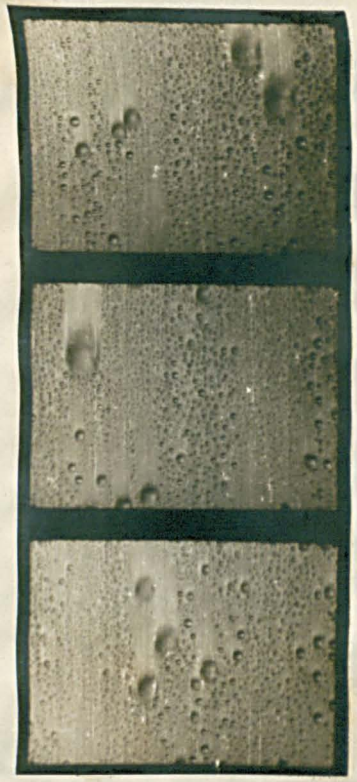


(e) 48 hrs.

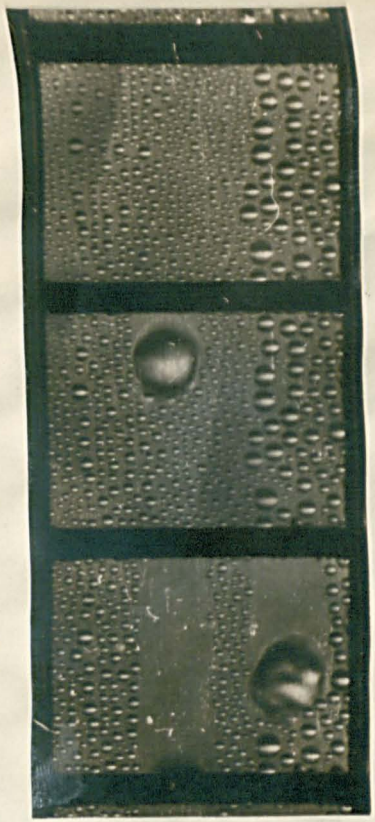
Plate(5.2) Progress of a Stainless Steel surface promoted with a mixture of oleic acid and a light lubricating oil.



(a) Before injection.



(b) Shortly after injection. Drops are extremely fine grained and running down at a fast rate.



(c) Surface resumed its normal appearance a few seconds later.

Plate (5.3) Change in appearance of Drop Formation following the injection of Trichloroethylene.

CHAPTER 6.

HEAT TRANSFER THROUGH INDIVIDUAL DROPLETS

(1) Statement of the Problem and Simplified Assumptions.

(2) Numerical Solutions by the Relaxation Method.

(3) Approximate Heat Conduction through Droplets.

(1) Statement of the Problem and Simplified Assumptions

In dropwise condensation, about 50-60% of the total condensing surface is covered by drops of visible size (say, drops over 0.005 inch diameter). Heat transmission through these drop-covered areas is limited by the heat resistance of the drops. In order to ascertain to what extent the drop-covered areas contribute to the total heat transmission, it is necessary to know the heat resistance of the drops. In the present chapter a method is described to evaluate the approximate heat transmission through individual droplets.

Fig. (6.1) shows a single droplet resting on the condensing surface and meeting it at a certain contact angle ϕ . The exact shape for drops hanging from a horizontal surface is theoretically known. Their boundary surface is found to be nearly the same as the segment of a sphere, as can be seen in Fig. (6.2), where the solid outlines show the exact shape and dotted lines are circular arcs. Owing to mathematical difficulties, the exact shapes for the drops formed on surfaces of other inclinations

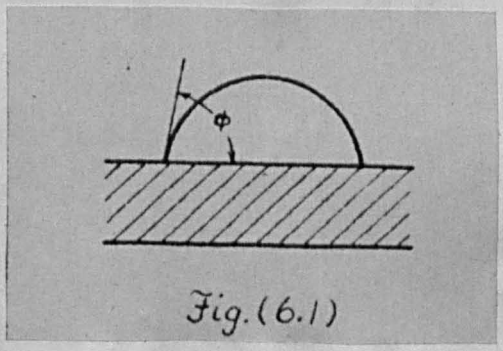


Fig. (6.1)

are not theoretically known. But observations and photography of drops on some inclined surfaces on which rapid condensation takes place indicates that drops of all sizes on them must also approximate very closely to a spherical form. In the following analysis to find the heat transmission through drops, the drops are assumed to be of the shape of spherical segments.

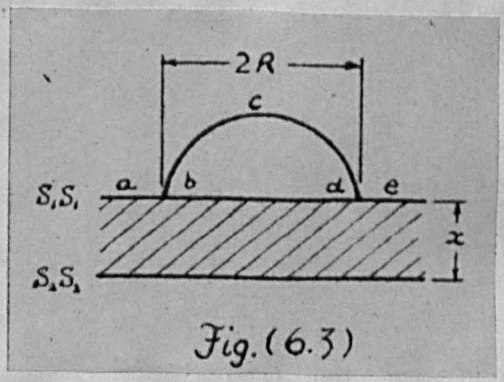


Fig.(6.3)

In Fig.(6.3) S_1S_1 and S_2S_2 are respectively the steam side and the water side surface of the metal plate. As has been explained in Chapter 4, the local steam side surface temperature is subjected to periodical fluctuation which will be more or less damped by the metal plate. If the metal plate is thick, the fluctuation may be completely damped out before reaching its water side surface. On the other hand, if the plate is thin, the fluctuation may penetrate into the viscous film on the water side. While the exact depth of penetration could not be readily found, it must be a closer approximation to choose the water side surface (S_2S_2), instead of the steam side surface (S_1S_1), as one of the isothermal surfaces. The other isothermal surface is

chosen as *abcde*, i.e., the liquid-steam interface with extension to include the neighbouring steam side surface of the metal plate. This means that in the following analysis, the heat resistance of a droplet is considered in conjunction with the resistance of the metal plate on which the droplet is resting.

Heat conduction between these two isothermal surfaces involves a discontinuity of material (from water to metal). For simplicity, the metal plate is replaced by an <u>equivalent</u> thickness of water in reverse proportion to their thermal conductivities. Strictly speaking, this way of dealing with material discontinuity in heat conduction problems does not give a theoretically exact result. However it is considered that it does not involve any appreciable error in the present case since the direction of heat flow is chiefly one <u>across</u> the plate. Thus if

x = the thickness of the metal plate,

K = the thermal conductivity of water,

K' = the thermal conductivity of the metal.

We have the equivalent thickness of the plate

$$x_e = x \times \frac{K}{K'} \qquad (6.1)$$

For future convenience, let α represent the ratio between the equivalent thickness of the plate and the radius of the droplet, i.e.,

$$\alpha = x_e / R \qquad (6.2)$$

Under these simplified assumptions, our problem is reduced to finding the heat conduction between two isothermal surfaces abcde and fg, Fig. (6.4.)

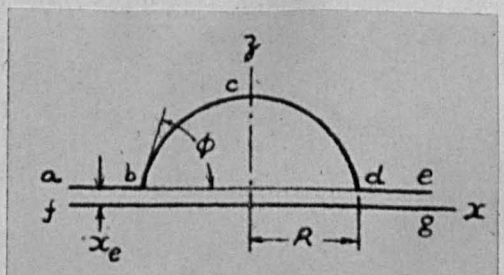


Fig.(6.4)

It is understood that bcd is a spherical surface, ϕ is the contact angle, and x_e the <u>equivalent</u> thickness of the metal plate.

The fundamental equation for steady state heat conduction is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 , \qquad (6.3)$$

where T represents temperature and x, y, z are coordinate axes. For bodies having a symmetrical axis z, eqn.(6.3) can be reduced to the following two dimensional equation in any meridian section plane:

$$\frac{\partial^2 T}{\partial x^2} + \frac{1}{x}\frac{\partial T}{\partial x} + \frac{\partial^2 T}{\partial z^2} = 0 \qquad (6.4)$$

The boundary conditions are, referring to Fig.(6.4) :

$$\left.\begin{aligned} T &= 0 \qquad \text{along} \quad abcde \\ T &= \Delta t \qquad \text{along} \quad fg \end{aligned}\right\} \tag{6.5}$$

It is not possible to find the exact solution which satisfies eqn.(6.4) and also the given boundary conditions (6.5). In the following it is proposed to work out the numerical solution for a few representative cases by the relaxation method. Then we proceed to find a general expression which gives a result in approximate agreement with that by the relaxation method.

(2) Numerical Solutions by the Relaxation Method.

Eqn. (6.4) is among those equations which can be numerically solved by the relaxation method [29]. This was done by reducing it to a corresponding finite difference equation. It is convenient to use a square net in the relaxation treatment of the present problem. Referring to Fig.(6.5), if "a" be the side of the square, we have

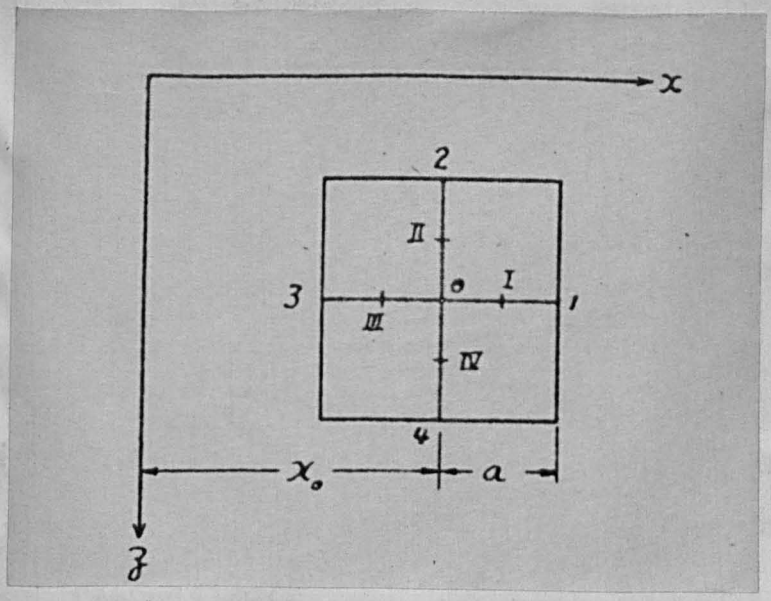


Fig. (6.5)

$$\left(\frac{\partial^2 T}{\partial x^2}\right)_0 = \frac{1}{a}\left[\left(\frac{\partial T}{\partial x}\right)_I - \left(\frac{\partial T}{\partial x}\right)_{III}\right],$$

$$\left(\frac{\partial T}{\partial x}\right)_I = \frac{1}{a}\left(T_1 - T_0\right),$$

$$\left(\frac{\partial T}{\partial x}\right)_{III} = \frac{1}{a}\left(T_0 - T_3\right),$$

Hence $$\left(\frac{\partial^2 T}{\partial x^2}\right)_0 = \frac{1}{a^2}\left(T_1 + T_3 - 2T_0\right).$$

Similarly $$\left(\frac{\partial^2 T}{\partial z^2}\right)_0 = \frac{1}{a^2}\left(T_2 + T_4 - 2T_0\right),$$

and $$\frac{1}{x_0}\left(\frac{\partial T}{\partial x}\right)_0 = \frac{1}{2ax_0}\left(T_1 - T_3\right).$$

Adding up the last three equations, we have the required finite difference equation:

$$T_1\left(1 + \frac{a}{2x_0}\right) + T_2 + T_3\left(1 - \frac{a}{2x_0}\right) + T_4 - 4T_0 = 0. \qquad (6.6)$$

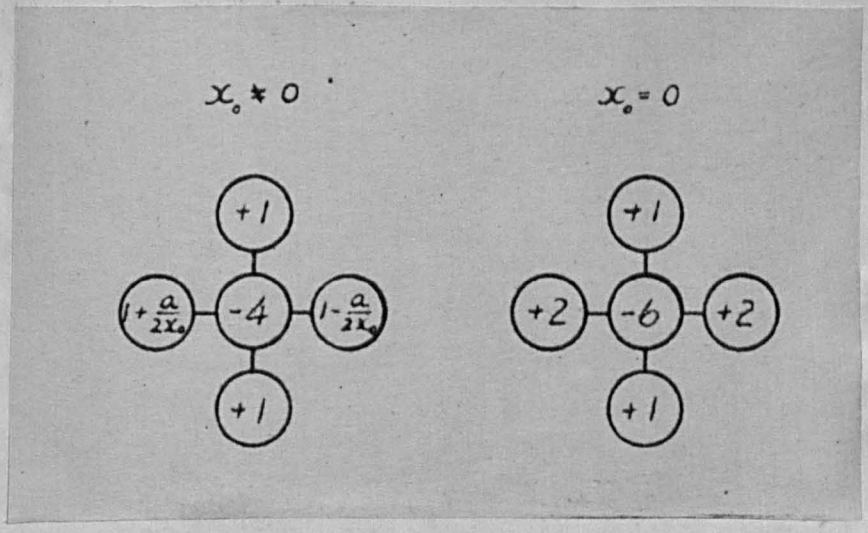
At $x = 0$, we have $\lim_{x \to o} \frac{1}{x} \frac{\partial T}{\partial x} = \frac{\partial^2 T}{\partial x^2}$, hence eqn.(6.4) reduces to

$$2 \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = 0 , \qquad (6.4a)$$

the corresponding finite difference equation for which is

$$2 T_1 + T_2 + 2 T_3 + T_4 - 6 T_o = 0 . \qquad (6.6a)$$

The relaxation pattern is directly derived from eqn. (6.6) and eqn.(6.6a) and is given in the following for $x \neq o$ and $x = o$ respectively



Detailed working procedure need not be described here. Suffice it to say that from the relaxation method a series of isothermal lines can be obtained. And quantitatively the amount of heat conduction (q) through the droplet can be evaluated by integrating along its boundary surface the following integral :

$$q = \int K \left(\frac{\partial T}{\partial n} \right) dA \qquad (6.7)$$

where $\frac{\partial T}{\partial n}$ = the normal temperature gradient across the boundary surface.

K = the thermal conductivity of water,

dA = the elementary boundary surface.

Figs.(6.6),(6.7),(6.8) show the results of computation by the relaxation method for some representative values of α and ϕ. Isothermal lines were drawn and the heat conduction (q) through the droplet was evaluated according to eqn.(6.7) in each case.

It should be appreciated that the numerical solution of eqn.(6.4) by the relaxation method described above involved a considerable amount of work for each combination of α and ϕ. It is impracticable to apply this method to more than a limited number of representative values of α and ϕ. Therefore it best serves as a reference for checking purposes rather than as a direct means of solving the present problem. In the next section, an approximate method is described to evaluate the heat conduction through individual droplets for any value of α and ϕ. Its degree of accuracy will be tested by comparing it with the results from the relaxation method as have already been worked out and given in Figs.(6.6), (6.7),(6.8).

(3) Approximate Heat Conduction through Droplets

Approximate heat conduction through droplets is evaluated in this section by assuming a series of curves as heat flow lines. Based on this assumption, an equation is derived which gives the approximate heat conduction through droplets. Its degree of accuracy is discussed in the later part of this section.

The assumed heat flow lines are constructed in the following manner. In Fig.(6.9), PS is the tangent to the liquid surface at any point P, and it intersects S_1S_1 at S. The assumed heat flow line through P is PQT, where PQ is a circular arc having S as its centre, and QT is a short straight line extension.

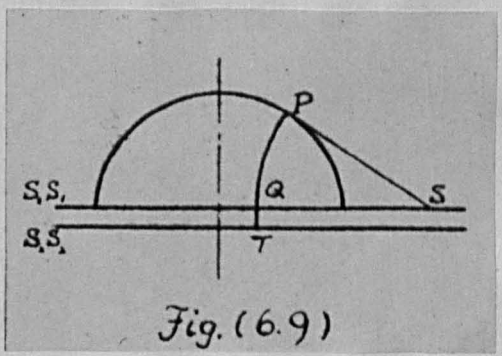


Fig.(6.9)

Having these assumed heat flow lines, it is a simple matter to work out the amount of heat (q) conducted through the area πR^2 occupied by the droplet. Consider, in Fig. (6.10), the heat conduction dq through an elementary shell of which $PP'T'T$ is its meridian section, we have

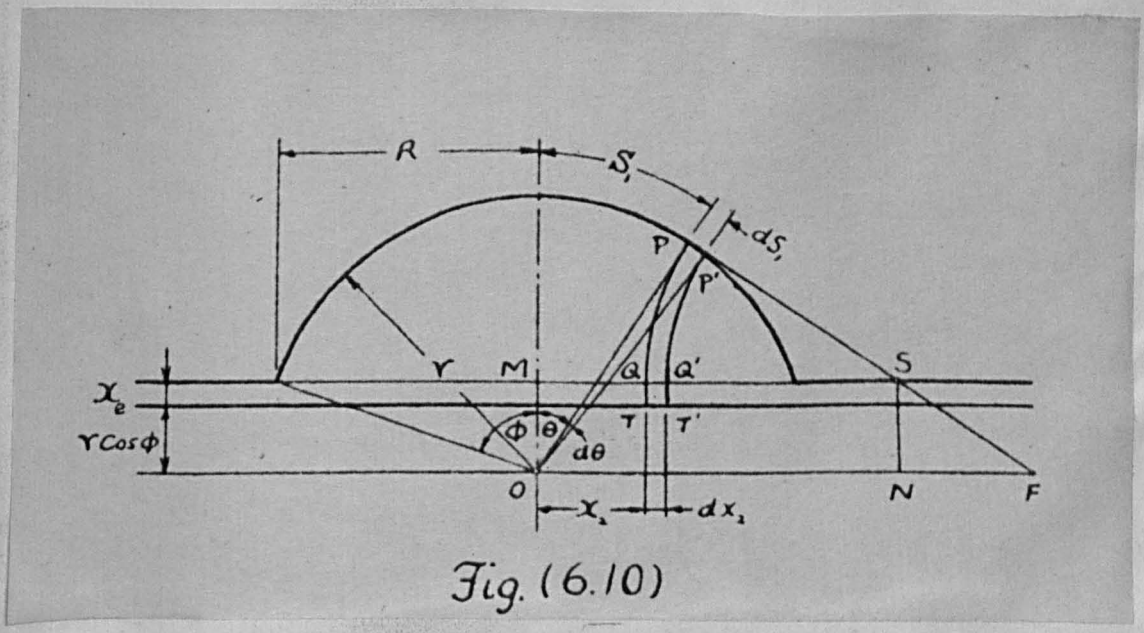


Fig. (6.10)

$$dq = K A_m \frac{\Delta t}{l}$$

where K = the thermal conductivity of water,

Δt = The temperature difference between steam and the water side surface,

l = the length of heat flow path $\widehat{PQT}$,

A_m = the mean cross-sectional area of the elementary shell. It is taken as the arithmetic mean of the areas at either end of the shell, i.e.,

$$A_m = \tfrac{1}{2}(2\pi x_1 dS_1 + 2\pi x_2 dx_2) = \pi(x_1 dS_1 + x_2 dx_2).$$

Now $x_1 = r \sin\theta$,

$S_1 = r\theta$, $dS_1 = r d\theta$,

$x_2 = \overline{MQ} = \overline{MS} - \overline{QS} = (\overline{OF} - \overline{NF}) - \overline{PS}$

$= (r\csc\theta - r\cos\phi \cot\theta) - (r\cot\theta - r\cos\phi\csc\theta) = r(1+\cos\phi)\tan\frac{\theta}{2}$,

$dx_2 = \frac{1}{2} r (1+\cos\phi) \sec^2\frac{\theta}{2}\, d\theta$.

$$\therefore \quad A_m = \pi r^2 \left[\sin\theta + \tfrac{1}{2} \tan\tfrac{\theta}{2} \sec^2\tfrac{\theta}{2} (1+\cos\phi)^2 \right] d\theta ,$$

and $$\ell = r\theta \left(\cot\theta - \cos\phi \csc\theta \right) + x_e .$$

Substituting A_m and ℓ into $dq = K A_m \frac{\Delta t}{\ell}$ and simplifying, we have

$$dq = \pi K \Delta t \frac{R}{\sin\phi} \cdot \frac{\sin\theta + \frac{1}{2} \tan\frac{\theta}{2} \sec^2\frac{\theta}{2} (1+\cos\phi)^2}{\frac{\theta}{\sin\theta} (\cos\theta - \cos\phi) + \alpha \sin\phi} ,$$

where $\alpha = x_e / R$ (see eqn.6.2).

Therefore $$q = \pi K \Delta t \frac{R}{\sin\phi} \int_0^{\phi} \frac{\sin\theta + \frac{1}{2} \tan\frac{\theta}{2} \sec^2\frac{\theta}{2} (1+\cos\phi)^2}{\frac{\theta}{\sin\theta} (\cos\theta - \cos\phi) + \alpha \sin\phi} d\theta . \qquad (6.8)$$

When $\phi = 90^\circ$, eqn.(6.8) becomes

$$q = \pi K \Delta t R \int_0^{\frac{\pi}{2}} \frac{\sin\theta + \frac{1}{2} \tan\frac{\theta}{2} \sec^2\frac{\theta}{2}}{\theta \cot\theta + \alpha} d\theta . \qquad (6.9)$$

Eqns.(6.8),(6.9) can be numerically integrated by any standard formulas such as six-strip formula. The result is shown in Fig.(6.11) where the dimensionless term $q / K \Delta t R$ is plotted against α (in the range $0 < \alpha < 0.1$)for three values of contact angle ($\phi = 45^\circ$, 60°, and 90°).

The accuracy of the value of q calculated according to eqn.(6.8) depends on how far the assumption of heat flow lines is true. It is to be noted that the value of q so calculated is always higher than its correct value.

This is because in the region where most heat conduction takes place, the assumed heat flow path PS is always shorter than its correct path PS' Fig.(6.12). When α is very small (in other words, when the equivalent thickness of the plate is small compared with the size of the droplet), the error is negligible. The error increases when the equivalent thickness of the plate approaches the same order as the size of the droplet.

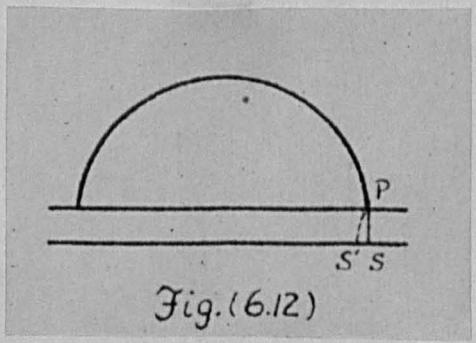


Fig.(6.12)

In Figs.(6.6),(6.7),(6.8) are shown the assumed heat flow lines drawn in the manner described above. When $\alpha = 0.01$, Fig.(6.6) shows the assumed heat flow lines are nearly othogonal to the isothermal lines everywhere except in a small region where the droplet meets the relatively plane metal surface. In this case, the value of q calculated according to eqn.(6.8) is correct to 3%. In Fig.(6.7), $\alpha = 0.1$, the equivalent thickness of the plate is appreciable compared with the size of the droplet. In this case the value of q calculated according to eqn.(6.8) is 8% too high. Hence it can be concluded that in the range of $0 < \alpha < 0.1$, eqn.(6.8) can be used to evaluate the heat conduction through droplets to within, say, 10% accuracy.

It should be appreciated that this range of α ($0<\alpha<0.1$) would cover all droplets over 0.005 inch diameter on a $\frac{1}{8}$ inch thick copper or a $\frac{1}{32}$ inch thick brass plate.

It is not recommended to use eqn.(6.8) for $\alpha > 0.1$. For instance, when $\alpha = 1$, the error involved is considerable (in the order of + 30%). Therefore in these cases eqn.(6.8) cannot be applied without suitable correction. When a correction factor f is applied, eqn.(6.8) becomes

$$q = f \pi K \Delta t \frac{R}{\sin\phi} \int_0^{\phi} \frac{\sin\theta + \frac{1}{2}\tan\frac{\theta}{2}\sec^2\frac{\theta}{2}(1+\cos\phi)^2}{\sin\theta\,(\cos\theta-\cos\phi)+\alpha\sin\phi}\, d\theta \qquad (6.10)$$

The correction factor f can take any simple and convenient form, but if the following values are used:

$$f = \frac{2}{3}(1+e^{-\alpha}) \quad \text{for} \quad \phi = 90^\circ,$$

$$\frac{1}{7}(6+e^{-\alpha}) \quad " \quad \phi = 60^\circ,$$

$$\frac{2(1+\cos\phi)+(1-\cos\phi)e^{-\alpha}}{3+\cos\phi} \quad " \quad \text{any } \phi,$$

eqn.(6.10) will be correct to within 10% for the range $0<\alpha<1$ and also correct in the limiting case when α approaches infinity.

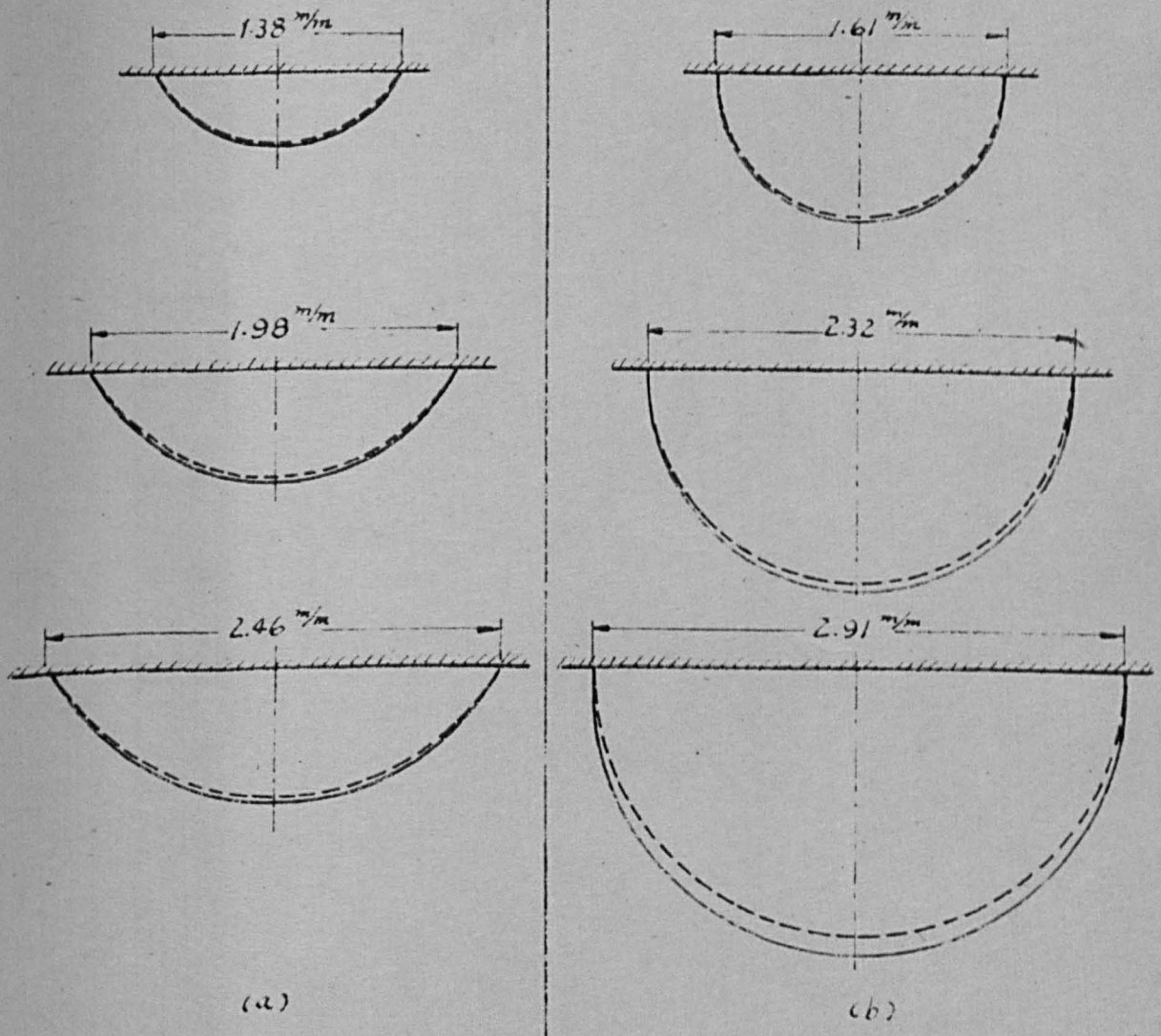


Fig.(6.2). Comparison between the true shape of a small hanging drop and a spherical shape.

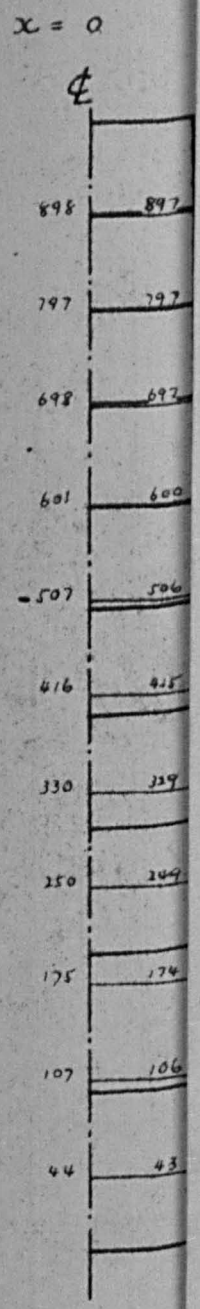

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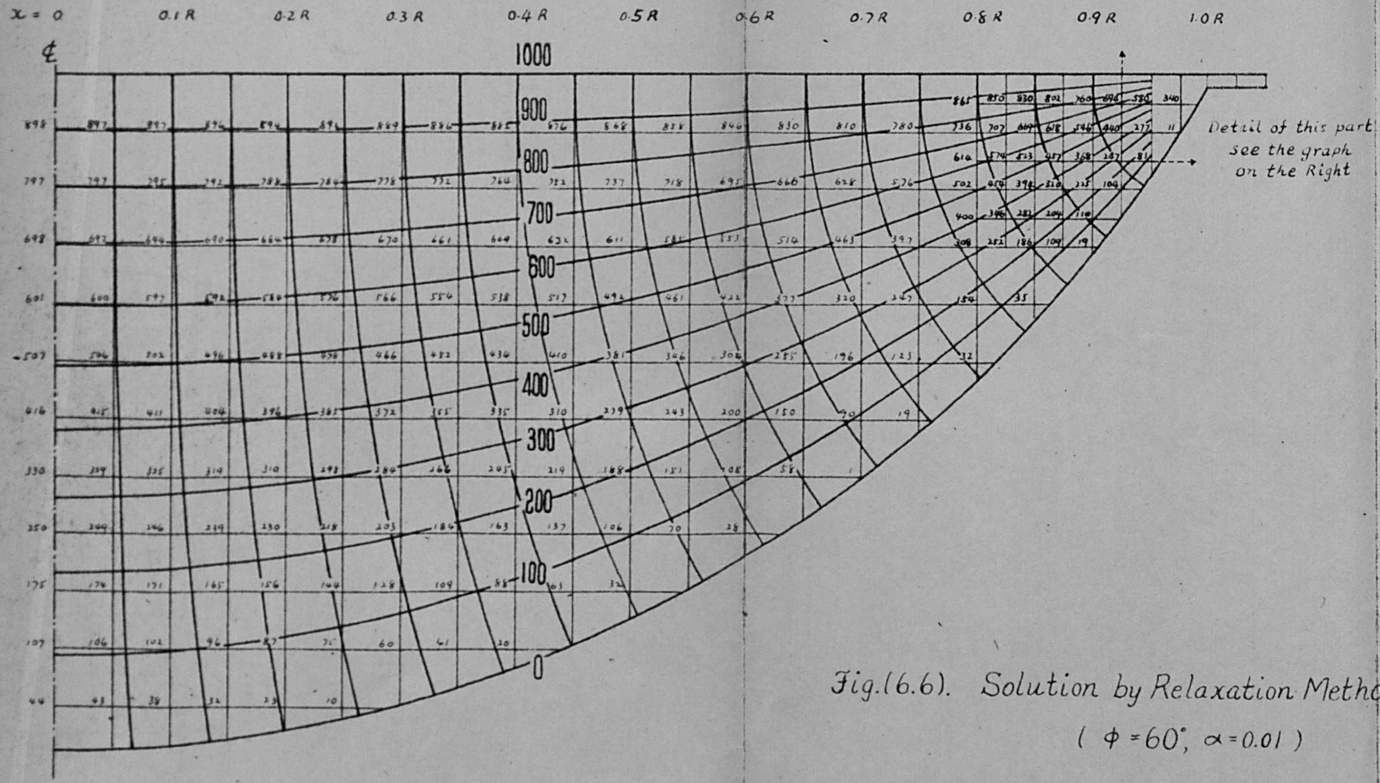
Fig. (6.6)



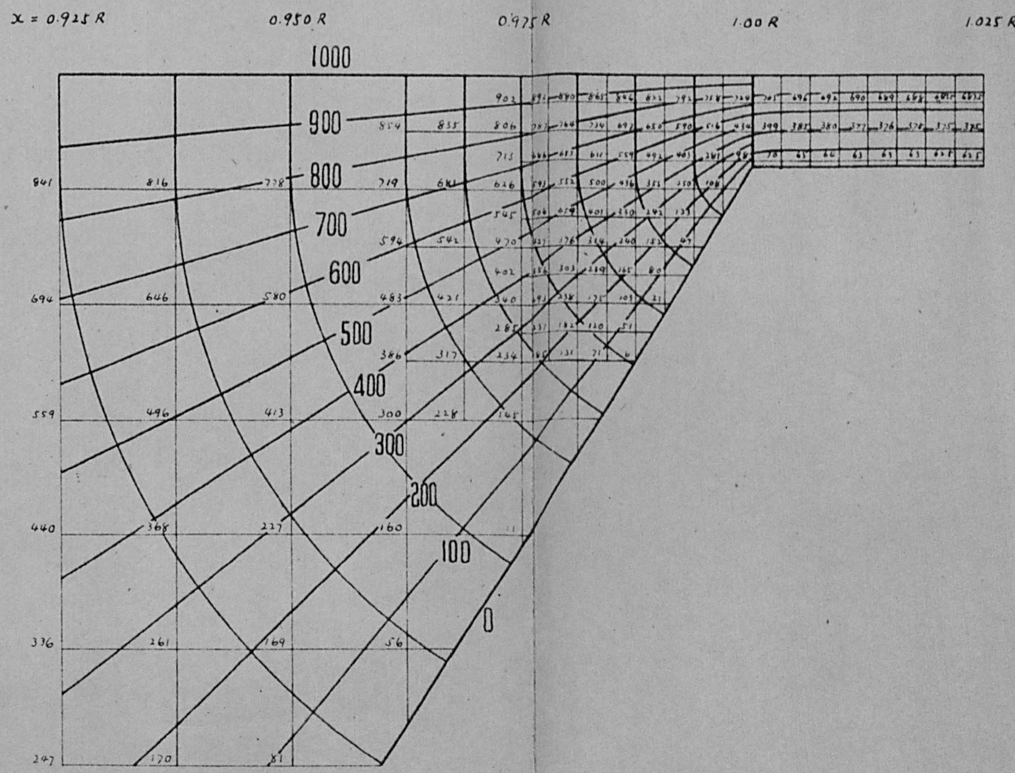


Fig.(6.6). Solution by Relaxation Method.

($\phi = 60°$, $\alpha = 0.01$)

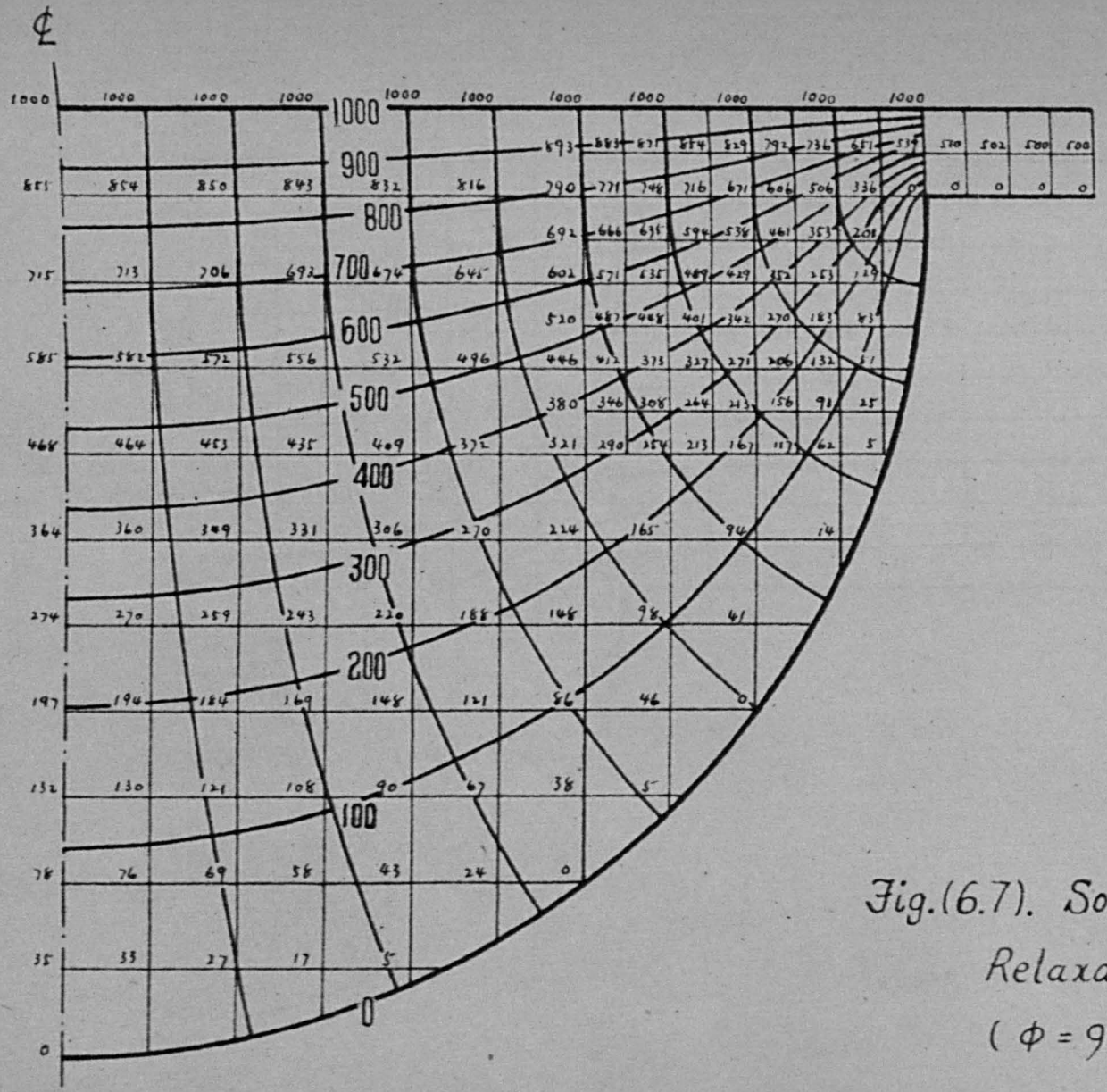


Fig.(6.7). Solution by Relaxation Method.

($\phi = 90°$, $\alpha = 0.1$)

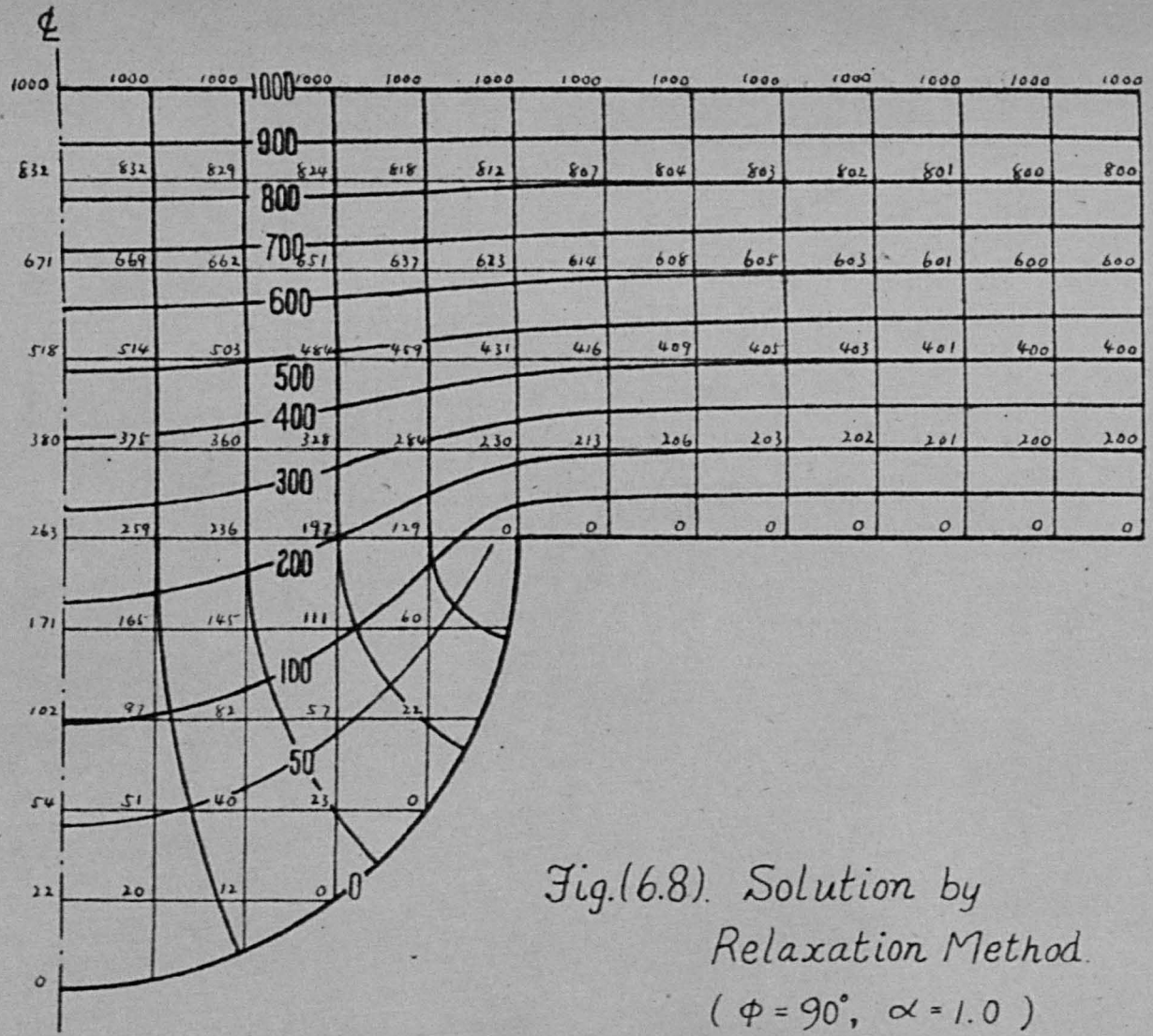


Fig.(6.8). Solution by Relaxation Method.

($\Phi = 90°$, $\alpha = 1.0$)

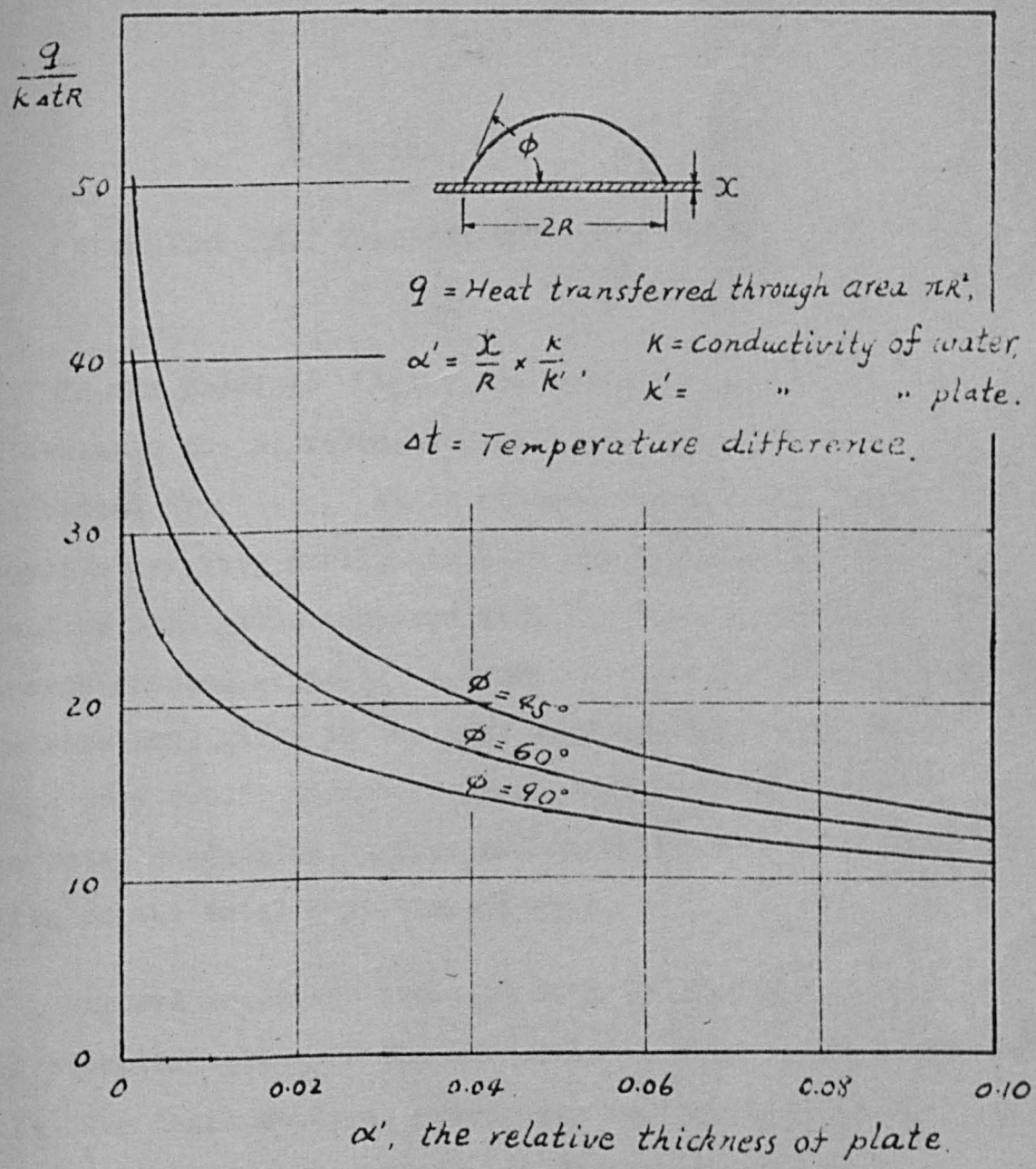


Fig.(6.11). Heat transfer through drops

CHAPTER 7

TRANSIENT HEAT TRANSFER THROUGH EXPOSED AREAS

In the previous Chapter, an analysis has been given to evaluate the approximate heat conduction through individual droplets. It is expected that unless the droplets are very small, the heat transmission through them would be negligible compared with the heat transferred through exposed areas. A study of statistical drop size distribution, given in the next Chapter, indicates that drops over 0.005" diameter occupy just over one half of the total condensing surface and contribute ~~to~~ about one fifth of the total heat transmission.

Exposed areas are produced both by coalescence and by the sweeping action of the down rolling drops. In either case, the local surface, previously covered by a droplet, is brought into direct contact with the condensing steam. Consequently the local surface temperature is suddenly raised from a lower value to nearly that of the steam as has been explained in Chapter 4 . The heat transmission through those exposed areas must take place in an unsteady state, and is limited by the resistance of the metal plate and the water side resistance.

In this Chapter, an analysis is made to investigate the transient heat transfer through a metal plate when its steam side surface temperature is suddenly raised from T_1' to T_1 Fig.(7.1). Its water side surface temperature is assumed to be anchored to a fixed value T_1, and the initial temperature distribution is assumed to be linear. For simplicity, the heat flow is assumed to be one dimensional, although actually there may be some heat flow of lesser importance in transverse directions due to the unevenness of the steam side surface temperature.

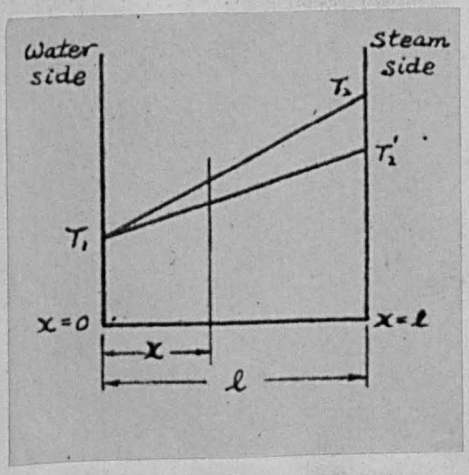


Fig. (7.1)

The fundamental equation for one dimensional heat conduction is

$$\frac{\partial T}{\partial \theta} = k^2 \frac{\partial^2 T}{\partial x^2} \qquad (7.1)$$

where T = temperature;

θ = time;

$k^2 = \frac{K'}{c\rho}$ = the thermal diffusivity of the metal;

and K' = the thermal conductivity,

c = the specific heat,

ρ = the density of the metal.

Referring to Fig.(7.1), the boundary conditions are:

$$T = T_1 \quad \text{at} \quad x = 0 , \tag{7.2}$$

$$T = T_2 \quad \text{at} \quad x = \ell , \tag{7.3}$$

$$T = T_1 + (T_2' - T_1)\frac{x}{\ell} \quad \text{when} \quad \theta = 0, \tag{7.4}$$

(initial temperature distribution)

$$T = T_1 + (T_2 - T_1)\frac{x}{\ell} \quad \text{when} \quad \theta = \infty . \tag{7.5}$$

(final steady state temperature distribution)

It can be proved that the following series

$$T = T_1 + (T_2 - T_1)\frac{x}{\ell} + A_1 e^{-k^2\frac{\pi^2}{\ell^2}\theta} \sin\frac{\pi x}{\ell} + A_2 e^{-k^2\frac{4\pi^2}{\ell^2}\theta} \sin\frac{2\pi x}{\ell} + \cdots \tag{7.6}$$

satisfies the fundamental differential equation (7.1) as well as the boundary conditions (7.2),(7.3), and 7.5). The constants A_1, A_2, $\cdots$ can be so determined as to make eqn.(7.6) satisfy the boundary condition (7.4). Since for $\theta = 0$, eqn.(7.6) becomes

$$T = T_1 + (T_2 - T_1)\frac{x}{\ell} + A_1 \sin\frac{\pi x}{\ell} + A_2 \sin\frac{2\pi x}{\ell} + \cdots . \tag{7.7}$$

Equating eqns.(7.4) and 7.7), gives

$$(T_2' - T_2)\frac{x}{\ell} = A_1 \sin\frac{\pi x}{\ell} + A_2 \sin\frac{2\pi x}{\ell} + A_3 \sin\frac{3\pi x}{\ell} + \cdots . \tag{7.8}$$

in which A_1, A_2, ... can be determined by Fourier integrals.

In general,

$$A_n = \frac{2}{\ell} \int_0^{\ell} (T_2' - T_2) \frac{x}{\ell} \sin \frac{n\pi x}{\ell} \, dx$$

$$= \frac{2}{\pi} (T_2' - T_2) \frac{(-1)^{n+1}}{n} .$$

Substituting the above values of A's, eqn.(7.6) becomes

$$T = T_1 + (T_2 - T_1)\frac{x}{\ell} - \frac{2}{\pi}(T_2 - T_2')\left[e^{-k^2 \frac{\pi^2}{\ell^2}\theta} \sin \frac{\pi x}{\ell} \right.$$

$$\left. - \frac{1}{2} e^{-k^2 \frac{4\pi^2}{\ell^2}\theta} \sin \frac{2\pi x}{\ell} + \frac{1}{3} e^{-k^2 \frac{9\pi^2}{\ell^2}\theta} \sin \frac{3\pi x}{\ell} - \cdots . \right] \qquad (7.9)$$

which is the required solution.

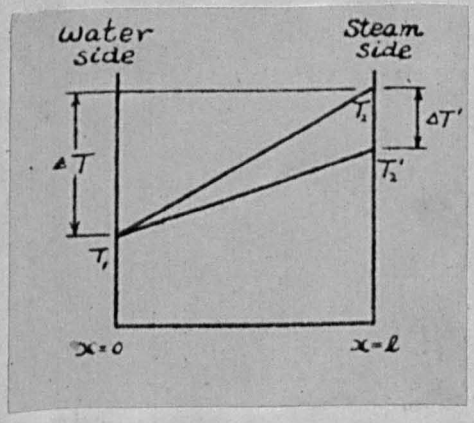


Fig.(7.2)

For convenience, refer to Fig (7.2) and let:-

$$T_2 - T_1 = \Delta T ,$$

$$T_2' - T_1 = \Delta T' ,$$

$$\Delta T' = \alpha \Delta T ,$$

where $0 < \alpha < 1$.

This reduces eqn.(7.9) into

$$T = T_1 + \Delta T \frac{x}{\ell} - \frac{2}{\pi} \Delta T' \left[e^{-k^2 \frac{\pi^2}{\ell^2}\theta} \sin \frac{\pi x}{\ell} \right.$$

$$\left. - \frac{1}{2} e^{-k^2 \frac{4\pi^2}{\ell^2}\theta} \sin \frac{2\pi x}{\ell} + \frac{1}{3} e^{-k^2 \frac{9\pi^2}{\ell^2}\theta} \sin \frac{3\pi x}{\ell} - \cdots . \right] \qquad (7.9a)$$

Differentiating the above equation (7.9a) with respect to x, gives the temperature gradient

$$\frac{\partial T}{\partial x} = \frac{\Delta T}{\ell} - 2\frac{\Delta T'}{\ell}\left[e^{-k^2\frac{\pi^2}{\ell^2}\theta}\cos\frac{\pi x}{\ell} - e^{-k^2\frac{4\pi^2}{\ell^2}\theta}\cos\frac{2\pi x}{\ell} + e^{-k^2\frac{9\pi^2}{\ell^2}\theta}\cos\frac{3\pi x}{\ell} - \cdots\right]. \quad (7.10)$$

The temperature gradient at the steam surface is obtained from the above equation by putting $x = \ell$, thus

$$\left(\frac{\partial T}{\partial x}\right)_\ell = \frac{\Delta T}{\ell} + 2\frac{\Delta T'}{\ell}\left[e^{-k^2\frac{\pi^2}{\ell^2}\theta} + e^{-k^2\frac{4\pi^2}{\ell^2}\theta} + \cdots\right]. \quad (7.11)$$

Or, expressed in dimensionless terms

$$\frac{\left(\frac{\partial T}{\partial x}\right)_\ell}{\frac{\Delta T}{\ell}} = 1 + 2\alpha\left[e^{-k^2\frac{\pi^2}{\ell^2}\theta} + e^{-k^2\frac{4\pi^2}{\ell^2}\theta} + \cdots\right], \quad (7.11a)$$

remembering that $\left(\frac{\partial T}{\partial x}\right)_\ell$ is the steam side surface temperature gradient at any time θ, and $\frac{\Delta T}{\ell}$ is its ultimate value at $\theta = \infty$ (steady state). In numerical calculations it is convenient to let

$$\theta = \frac{\ell^2}{\pi^2 k^2}\log\lambda. \quad (7.12)$$

If the above value of θ is substituted into eqns.(7.9a) and (7.11a), it gives

$$T = T_1 + \Delta T\frac{x}{\ell} - \frac{2}{\pi}\Delta T'\left[\frac{1}{\lambda}\sin\frac{\pi x}{\ell} - \frac{1}{2\lambda^4}\sin\frac{2\pi x}{\ell} + \frac{1}{3\lambda^9}\sin\frac{3\pi x}{\ell} - \cdots\right], \quad (7.9b)$$

and $$\left(\frac{\partial T}{\partial x}\right)_\ell = \frac{\Delta T}{\ell} + 2\frac{\Delta T'}{\ell}\left[\frac{1}{\lambda} + \frac{1}{\lambda^4} + \frac{1}{\lambda^9} + \cdots\right]. \quad (7.11b)$$

Fig.(7.3) shows how the temperature distribution across the metal plate changes with time. In Fig.(7.3) solid lines represent the initial and the ultimate temperature distribution, while the dotted lines represent the temperature distribution at intermediate stages. The intermediate time values θ_1 , θ_2 , ... are given in the accompanying table for different metals and their thicknesses. Fig.(7.4) shows how the steam side surface temperature gradient changes with time. The coordinates $\left(\frac{\partial T}{\partial x}\right)_\ell \Big/ \left(\frac{\Delta T}{\ell}\right)$ and $\theta \Big/ \left(\frac{\ell^2}{\pi^2 k}\right)$ used in this plotting are dimensionless. It can be seen that $\left(\frac{\partial T}{\partial x}\right)_\ell$ reaches its ultimate value $\left(\frac{\Delta T}{\ell}\right)$ at $\theta \Big/ \left(\frac{\ell^2}{\pi^2 k}\right) = 6$ approximately, for all values of α . The actual time scale for different metal plates are also shown in the accompanying table.

Our chief interest is in the transient heat flow through the exposed areas on the steam side surface which can be obtained by integrating eqn.(7.11) with respect to time. Thus, if the transient heat flow per unit area be represented by Q , we have

$$Q = K' \int_0^\theta \left(\frac{\partial T}{\partial x}\right)_\ell d\theta$$

$$= K' \int_0^\theta \left[\frac{\Delta T}{\ell} + 2\frac{\Delta T'}{\ell} \left\{ e^{-k\frac{\pi^2}{\ell^2}\theta} + e^{-k\frac{4\pi^2}{\ell^2}\theta} + \cdots \right\} \right] d\theta$$

$$= K' \left[\frac{\Delta T}{\ell}\theta - 2\frac{\Delta T'}{\ell}\left(\frac{\ell^2}{\pi^2 k}\right) \left\{ \left(e^{-k\frac{\pi^2}{\ell^2}\theta} + \frac{1}{4} e^{-k\frac{4\pi^2}{\ell^2}\theta} + \cdots \right) - \frac{\pi^2}{6} \right] . \qquad (7.13)$$

Putting $\theta = \frac{\ell^2}{k^2\pi^2} \log \lambda$ in the above equation, gives

$$Q = K'\left(\frac{\Delta T}{\ell}\right)\left(\frac{\ell^2}{\pi^2 k^2}\right)\left[\log \lambda + 2\alpha\left(\frac{\pi^2}{6} - \frac{1}{\lambda} - \frac{1}{4\lambda^4} - \frac{1}{9\lambda^9} - \cdots\right)\right] . \qquad (7.13a)$$

Fig.(7.5) shows the transient heat flow across a metal plate through exposed areas on the steam side surface. Dimensionless terms $Q \Big/ K'\left(\frac{\Delta T}{\ell}\right)\left(\frac{\ell^2}{\pi^2 k^2}\right)$ and $\theta \Big/ \left(\frac{\ell^2}{\pi^2 k^2}\right)$ are used in this plotting. It can be seen that the rate of heat flow decreases with time, and after a settling period (say $\theta \Big/ \left(\frac{\ell^2}{\pi^2 k^2}\right) = 3$), all the curves become virtually straight lines making 45° inclination with the axes.

One numerical example has been worked out in the following to show the transient rate of heat transfer in the exposed areas. Assuming saturated steam at $212^\circ F$ condenses on a standard $\frac{5}{8}$" diameter no.18 B.W.G.(0.049") brass tube cooled by water of $60^\circ F$ at 8 ft/Sec., the individual coefficients of heat transfer are estimated to be:

3750	B.t.u. / ft² - hr - °F			on water side,
14690	"	"	"	through brass tube,
25000	"	"	"	on steam side,

giving an overall coefficient 2670 B.T.u./ft² - hr - °F. The temperature drops are calculated from the above heat transfer coefficients, and are as follows:

$108.2^{\circ}F$ on water side,

$27.6^{\circ}F$ across brass tube.

$16.2^{\circ}F$ on steam side.

Hence in Fig.(7.1), $T_1 = 168.2^{\circ}F$,

$T_1' = 195.8^{\circ}F$,

$T_2 = 212.0^{\circ}F$.

For brass, we have $\ell^2 = 1.31 ft^2/hr$,

$K' = 60$ B.t.u./ft-hr-°F,

hence

$$\frac{\ell^2}{\pi^2 \ell^2} = 4.64 \times 10^{-3} \text{ Sec.},$$

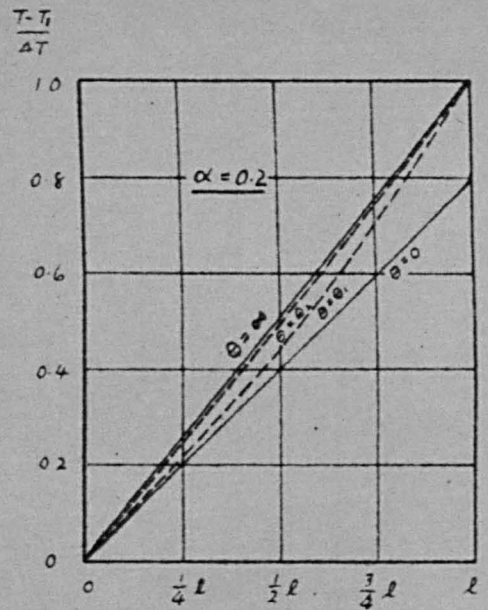
$$\frac{\Delta T}{\ell} = 10{,}720 \ ^{\circ}F/ft,$$

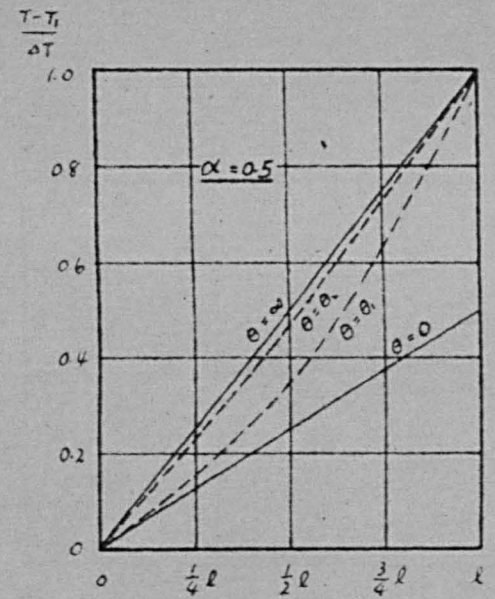
$$K'\left(\frac{\Delta T}{\ell}\right)\left(\frac{\ell^2}{\pi^2 \ell^2}\right) = 0.830 \text{ B.t.u./ft}^2.$$

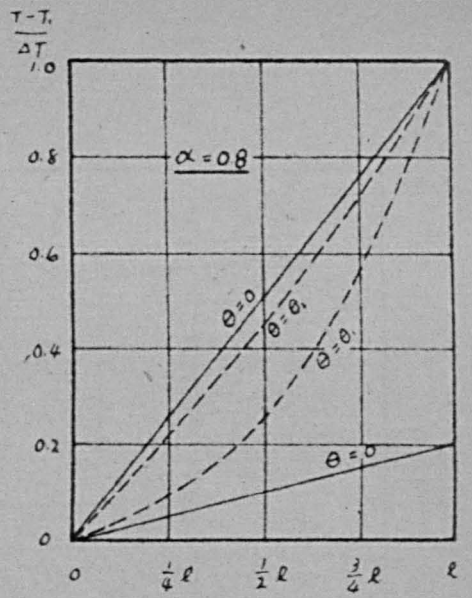
From the above data, (1) the temperature distribution across the wall of the tube, (2) the steam side surface temperature gradient, and (3) the rate of heat flow through exposed areas were calculated from eqns. (7.9b), (7.11b) and (7.13a) respectively. Figs.(7.6a) and (7.6b) show respectively how the temperature distribution across the tube wall, and the steam side surface temperature gradient change in response to the sudden rise of the steam side surface temperature. In Fig. (7.6c) the curved line L_1L_1 shows the transient rate of heat transfer through exposed areas, while the straight line L_2L_2 gives, in comparison, the average rate of heat transfer considering the steam side surface as a whole. The

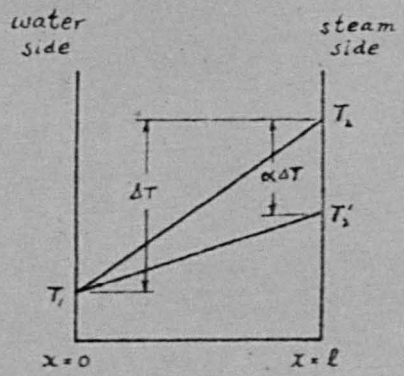
line L_3L_3 shows the rate of heat transfer in exposed areas if the temperature distribution across the tube wall reaches its final state instantaneously. The line L_4L_4 suggests the rate of increase in the thickness of the layer of water film which is believed to exist in the exposed areas prior to drop formation.

It should be noted that in the above analysis, the increasing resistance to heat flow due to the accumulation of the condensate layer was not considered. Since the resistance to heat conduction of a 0.0001" thick water film is comparable with that of the metal wall itself, the actual transient heat transfer through exposed areas would be lower than that indicated by the curve L_1L_1 in Fig.(7.6c). It should lie somewhere between the curve L_1L_1 and the straight line L_2L_2. Further analysis in this direction, taking into consideration also the heat resistance of the condensate layer, was contemplated by the present writer, but the greater mathematical complications required too long a time for their computation.









Thickness and metal of plate	$\theta_1 = \frac{\ell^2}{k^2\pi^2} \log 2$	$\theta_2 = \frac{\ell^2}{k^2\pi^2} \log 10$
$\frac{1}{16}$" Copper	0.0016 Sec.	0.0052 Sec.
$\frac{1}{8}$" —"—	0.0062 Sec.	0.021 Sec.
$\frac{1}{4}$" —"—	0.025 Sec.	0.084 Sec.
$\frac{1}{16}$" Brass	0.0052 Sec.	0.017 Sec.
$\frac{1}{8}$" —"—	0.021 Sec.	0.069 Sec.
$\frac{1}{4}$" —"—	0.084 Sec.	0.278 Sec.

Fig. (7.3) The Temperature Distribution Across the Plate

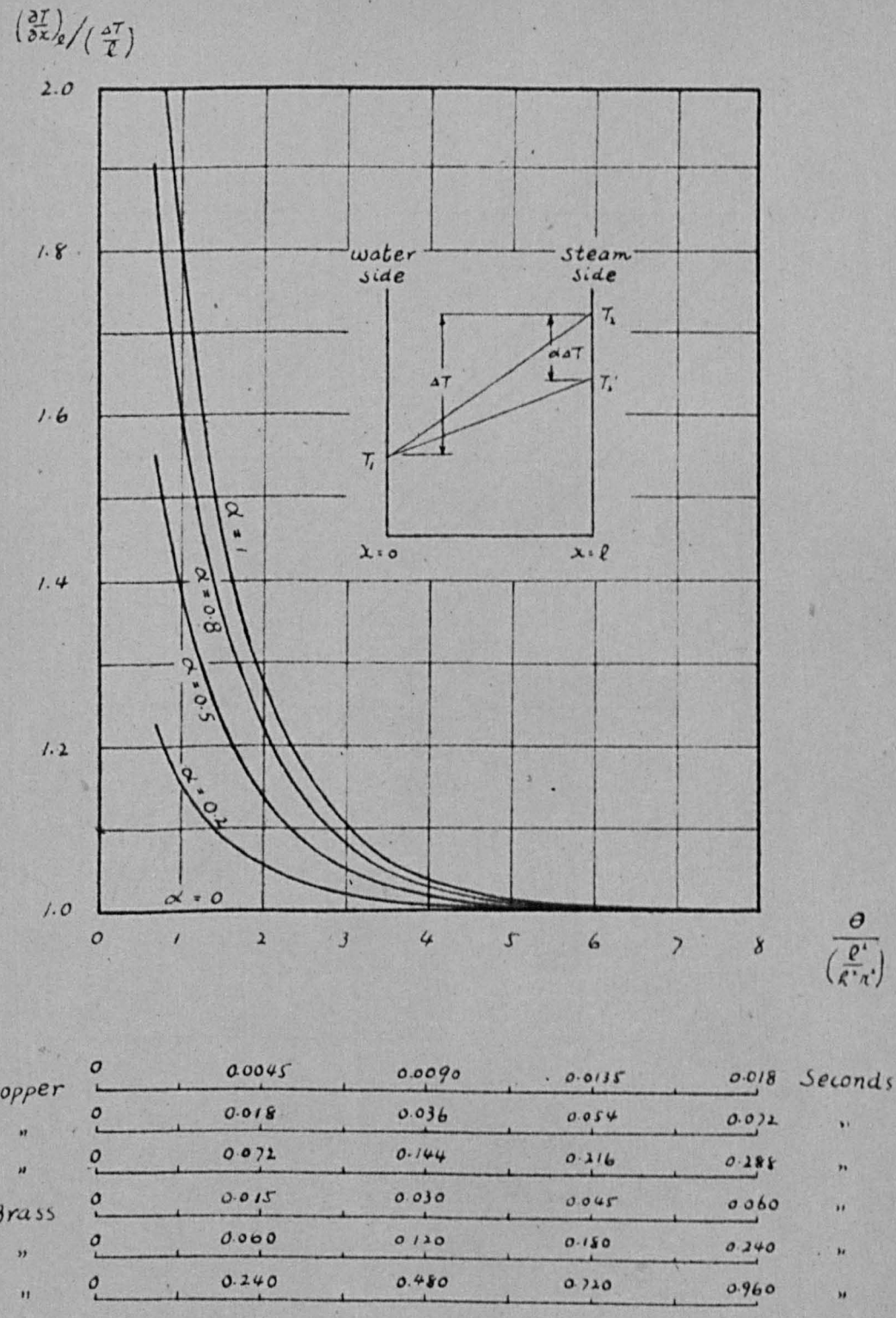


Fig. (7.4) The Temperature Gradient on the Steam Side Surface

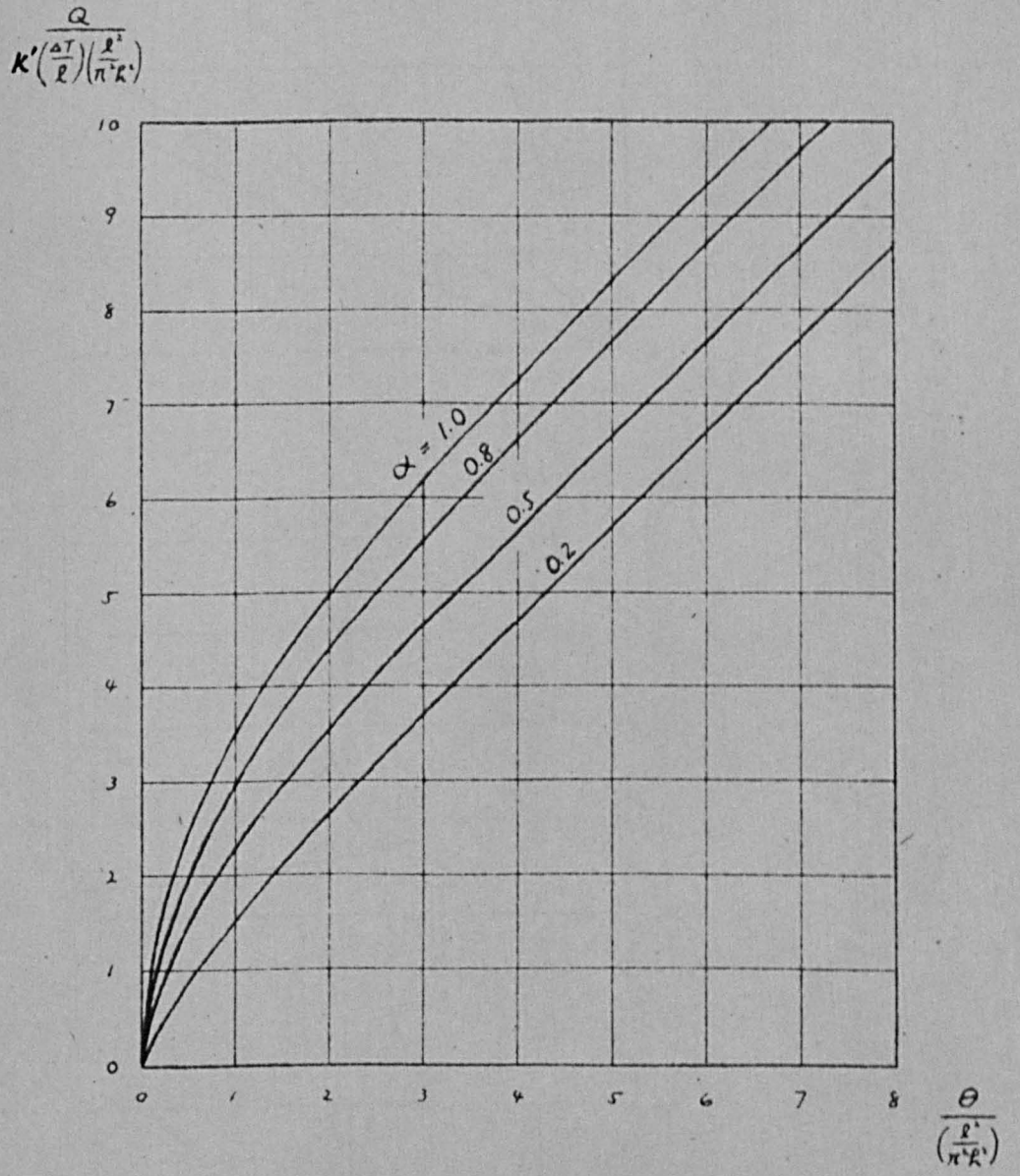


Fig.(7.5) Transient Heat Flow Across a Metal Plate through Exposed Areas.

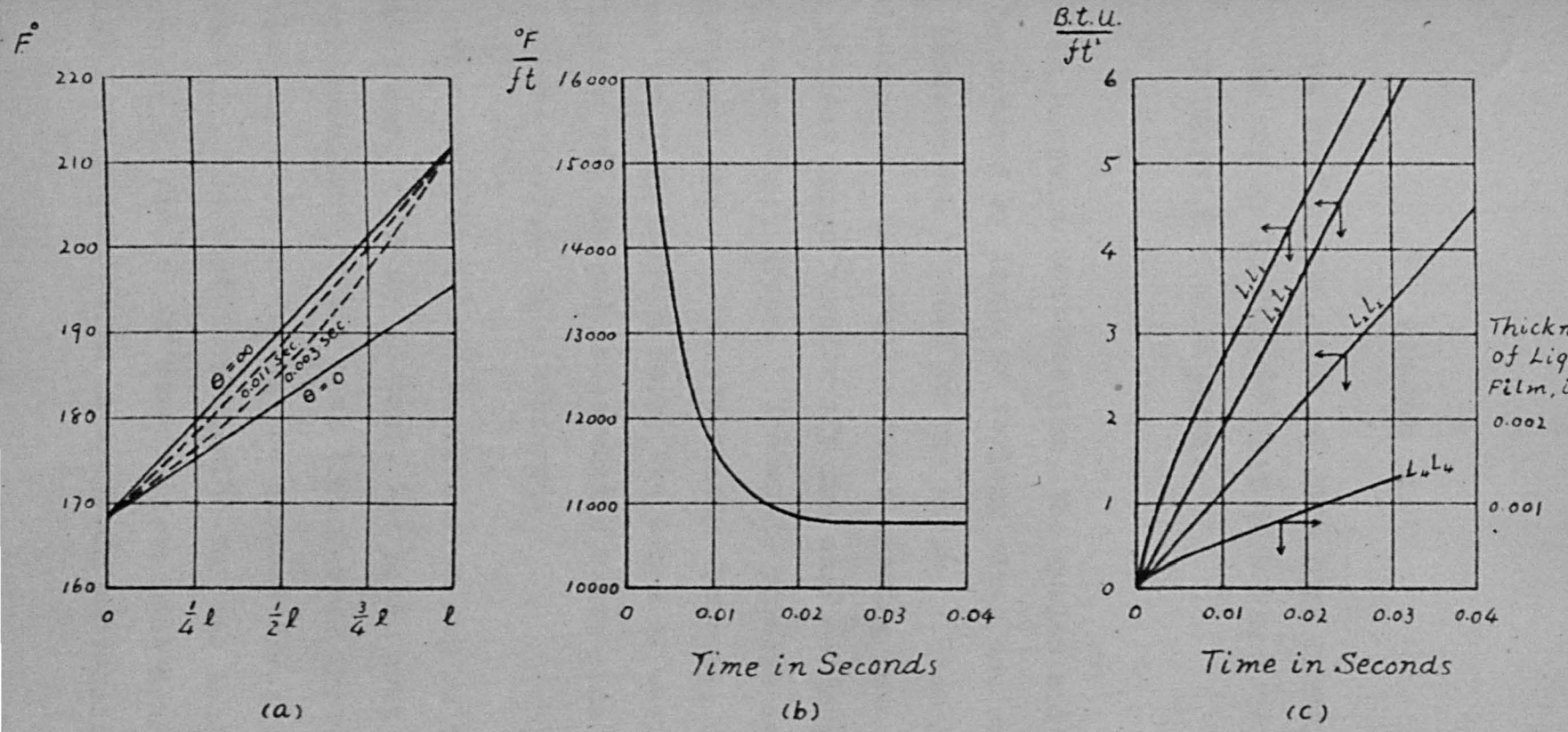


Fig. (7.6). Transient Heat Transfer Through Exposed Areas — A Numerical Example.

CHAPTER 8.

THE STATISTICAL STUDY OF DROP SIZE DISTRIBUTION AND THE ESTIMATION OF HEAT TRANSFER COEFFICIENTS IN DROPWISE CONDENSATION.

In dropwise condensation, the cooled surface is seen to be covered by drops of various sizes and some parts of the surface are exposed to the steam. Also the drops are coalescing; the smaller drops growing into bigger ones, the biggest drops running off the surface to give room again for the smallest drops. The whole process is, so to speak, a dynamical one. But presumably there is, at any instant, a regular distribution among the drops of various sizes including the exposed areas when a wider area of the condensing surface is considered.

The associated heat transmission may be looked at in a similar way. At any instant, the total heat transmission is the summation of the heat transferred through the drops of various sizes including the exposed areas. Considered statically, the heat transmission through them takes place according to the law of steady state heat conduction. The actual heat transmission in dropwise condensation is

further complicated by the rapid coalescence of the drops.

In this Chapter the method of finding the statistical drop size distribution is described. Based on the experimental drop size distribution, the heat transmission is evaluated by assuming that the drops are held at rest on the cooled surface and are conducting heat under steady state. The heat conduction through the individual drops depends on their size and shape, an analysis has been given in Chapter 6 for its approximate evaluation. In the exposed areas, the heat flow is limited by the metal plate only, and follows the ordinary law of uni-directional heat conduction under steady state. This gives the combined resistance of the condensate and the metal plate, or the combined coefficient of heat transfer from the steam to the water side surface of the metal plate. Let this combined coefficient of heat transfer be denoted by h_c . The steam side coefficient (h_s) can be separated from h_c by the following equation:

$$\frac{1}{h_s} = \frac{1}{h_c} - \frac{x}{K'} \qquad (8.1)$$

where K' and x are respectively the thermal conductivity and the thickness of the metal plate. It should be borne in mind that the steam side coefficient has been found in this

way by considering the heat transmission process as taking place among a certain distribution of stationary drops. The actual steam side coefficient in dropwise condensation may be further modified by the rapid motion of the drops.

Considering that the drops are moving fast on the condensing surface (but remain the same drop size distribution), then heat transmission must take place in an unsteady state. It has been shown in the previous Chapter (7) that in areas suddenly exposed to steam, the transient rate of heat transfer is higher than that given by steady state heat conduction. Conversely, in the area suddenly covered by a bigger drop, the transient rate of heat transfer through the steam side surface will be lower than that dictated by steady state heat flow. These two effects work in opposite directions. The heat capacity of the metal plate behaves much like a mechanical inertia, but in the long run its effect on heat transmission must be at most only of minor significance.

(1) The Statistical Study of Drop Size Distribution
--- Description of the Method and the Results.

An obvious way to find the drop size distribution experimentally is to take a picture of the condensing surface and count the drops. If a single picture is taken of a condensing surface at any instant and the number of drops of various sizes are counted, it would indicate a certain drop size distribution. Presumably this distribution is independent of the particular instant at which the picture is taken provided that the area covered by the picture is sufficiently big. If the picture does not cover a big enough area, then a number of pictures taken at equal intervals of time should be analyzed in order to establish a satisfactory average distribution.

Owing to the limited size of the present test surface (1" diameter disc), it was considered necessary to work out the distribution from the average of a number of cine'-picture frames. A 16mm aircraft gun camera, operating at 18 frames per second, was adapted for this purpose. It was focused to take pictures of about half natural size. Plate (8.1) shows the prints of one series of such pictures enlarged to about 1½ times natural size. But the actual counting was

performed on prints of 4.15 times natural size. Plate (8.2) shows one frame of them.

A graticule was required to facilitate the grouping of the drops into different ranges. To make this graticule, a negative and enlarged drawing of the graticule was laid down on drawing paper. A drawing of 4 times enlargement was found convenient and to give sufficient accuracy to the finished graticule. This drawing was photographed with a quarter plate Voigtlander camera focused to give exactly 4 times reduction so as to bring the graticule scale to the required size on the photographic plate. Kodak Maximum Resolution plate is satisfactory for this purpose owing to its high contrast and extremely fine grain emulsion. After processing, the emulsion side of the graticule was coated with a layer of cellulose to protect it from abrasion.

Plate (8.3) shows a contact print of the finished graticule. The dots on it were so arranged that the area is doubled in going from one size to the next bigger size, while size (0) is a dot of 1mm diameter. By means of this graticule, it is possible to group the drops on an average print up to the range " (-1) to (0)", while the drops in the range " (-2) to (-1)" can well be estimated.

It will be appreciated that size (-2) on a 4.15 times print corresponds to 0.12mm (roughly 0.005") diameter drops in their natural size.

The statistical study of drop size distribution was made on one drop promoting surface (namely, chromium plated copper surface treated with a mixture of oleic acid and a light lubricating oil) at three different rates of heat transmission later estimated to be roughly 200,000, 300,000, and 450,000 B.t.u. / ft^2-hr. The area covered by the picture is 218 sq.mm., and its position on the test surface is shown in Fig.(8.4). Preliminary trials showed that the average distribution of 8 to 16 frames corresponds fairly well with the average of more frames. Therefore it was considered enough to analyze and average a series of 32 frames for each rate of heat transmission. The results are shown in the following table. The table is self explanatory except the columns involving the term $\frac{dP}{dD}$ which is defined mathematically by the following expression:

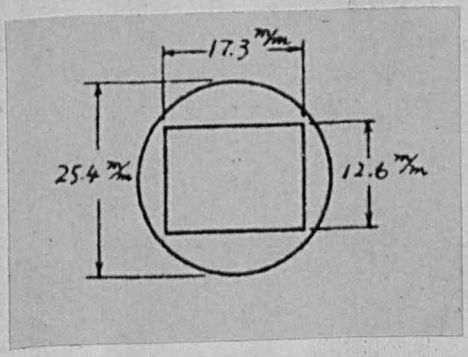


Fig.(8.4)

Statistical Drop Size Distribution

Steam: Saturated Steam at Atmospheric Pressure.
Dropwise Condenation on a Chromium Plated Surface Promoted With a Mixture of Oleic Acid and a Light Lubricating Oil.

Total Area Covered by Picture
218 Sq. mm.

	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮	⑯	⑰	⑱	⑲
								HEAT LOAD: 200,000 B.T.U./ft²-hr.				HEAT LOAD: 300,000 B.T.U./ft²-hr.				HEAT LOAD: 450,000 B.T.U./ft²-hr.			
Size of Drop, Referring to the Graticule Fig. (83)	Range of Diameters		Difference between D_{max} and D_{min}.		Geometrical Mean Diameter		Geometrical Mean Area per Drop, m/m^2	Average Number of Drops	Area, m^2/m^2	% Area	$\frac{dP}{dD}$	Average Number of Drops	Area m^2/m^2	% Area	$\frac{dP}{dD}$	Average Number of Drops	Area, m^2/m^2	% Area	$\frac{dP}{dD}$
	D_{max} m/m	D_{min} m/m	m/m	in.	m/m	in.													
			① - ②		$\sqrt{① \times ②}$		$\frac{\pi}{4} \times ⑤^2$		⑧ × ⑦	$\frac{⑨}{218} \times 100$	$\frac{⑩}{100 \times ④}$		⑫ × ⑦	$\frac{⑬}{218} \times 100$	$\frac{⑭}{100 \times ④}$		⑯ × ⑦	$\frac{⑰}{218} \times 100$	$\frac{⑱}{100 \times ④}$
-2 - -1	0.170	0.120	0.050	0.00197	0.143	0.0056	0.01615	557	9.01	4.13	20.95	729	11.76	5.39	27.35	498	8.05	3.69	18.72
-1 - 0	0.241	0.170	0.071	0.00279	0.202	0.0080	0.0323	267	8.63	3.96	14.20	266	8.60	3.95	14.15	282	9.11	4.18	14.99
0 - 1	0.341	0.241	0.100	0.00394	0.286	0.0113	0.0646	180	11.62	5.33	13.52	124	8.02	3.68	9.35	213	13.77	6.31	16.00
1 - 2	0.482	0341	0.141	0.00557	0.405	0.0160	0.1292	128	1655	7.59	13.61	89	11.50	5.27	9.46	118	15.25	6.99	12.52
2 - 3	0.682	0.482	0.200	0.00788	0.572	0.0226	0.2583	62	1601	7.35	9.32	58	14.98	6.86	8.71	59	15.25	6.99	8.86
3 - 4	0.764	0.682	0.282	0.0111	0.811	0.0319	0.5166	40	20.62	9.46	8.52	30.4	15.70	7.20	6.49	35	18.08	8.29	7.47
4 - 5	1.363	0.964	0.399	0.0157	1.145	0.0451	1.0333	22.0	22.74	10.42	6.64	13.3	13.75	6.31	4.02	13.8	14.27	6.54	4.16
5 - 6	1.928	1.363	0.565	0.0222	1.622	0.0638	2.066	7.5	15.50	7.11	3.20	5.2	11.27	5.16	2.32	3.7	7.65	3.51	1.58
6 - 7	2.726	1.928	0798	0.0314	2.290	0.0901	4.133	1.0	413	1.89	0.60	1.5	6.20	2.85	0.91	2.1	8.67	3.98	1.27
7 - 8	3.856	2.726	1.130	0.0445	3.244	0.1276	8.266	0.4	3.31	1.52	0.34	0.8	6.61	3.03	0.68	1.4	11.57	5.30	1.19
	Total Area Covered by Drops over 0.120 m/m Diameter								128.12	58.76%			108.39	49.70%			121.67	55.78%	
	Area unaccounted for								89.88	41.24%			109.61	50.30%			96.33	44.22%	

$\int_a^b \left(\frac{dP}{dD}\right) dD$ = the hatched area, Fig. (8.5)

= The fractional area covered by drops having diameter between a and b.

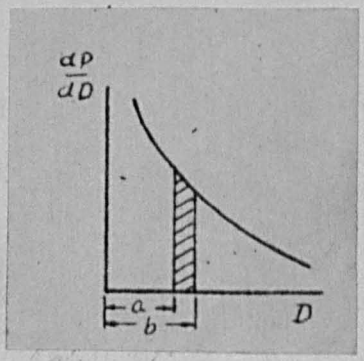


Fig. (8.5)

Fig. (8.6) shows the correspondence of the value of $\frac{dP}{dD}$ averaged from 32 frames with those averaged from 16 frames for the medium heat load. When $\frac{dP}{dD}$ is plotted against D for each heat load separately (Figs. 8.7a, 8.7b, and 8.7c), each assumes a simple curve. But when they are plotted on the same graph, the points are scattered and show no distinct trend for different rates of heat transmission. (Fig. 8.8). Therefore it must be either that the method used is inadequate to reveal the difference between different rates of heat transmission or, more probably, that there is in fact very little or no difference in drop size distribution between different heat transmission rates. The latter suggestion is plausible because if that is the case, then it is understandable that the steam side coefficient in dropwise condensation should be independent of the heat load, as shown by various investigators [10, 20, 26]. The drop size distribution remains practically the same, hence the same resistance to heat transmission for different heat

loads, only the drop formation occurs with faster speed at increased heat load.

The results also show that drops over 0.005" diameter occupy roughly 50% to 60%, averaging 55% of the total condensing surface. It follows that the remaining 45% area is covered by still smaller drops and some portion of it may be free surface. In the region of these small drops the distribution is not known, but the general tendency of the known portion of the distribution curve suggests it to go up with increasing steepness to make up the 45% area unaccounted for.

(2) Estimation of Heat Transfer Coefficient Based on the Experimental Drop Size Distribution.

Assuming that drop size distribution is independent of the heat load, and that a smooth curve drawn in Fig.(8.8) is accepted as due to an average drop size distribution, then the total heat transmission through the drops can be computed. In Fig.(8.9), let $\phi_1(D)$ represent the distribution curve taken from Fig.(8.8), and $\phi_2(D)$ represent the heat conduction through individual droplets obtained from Chapter 6.

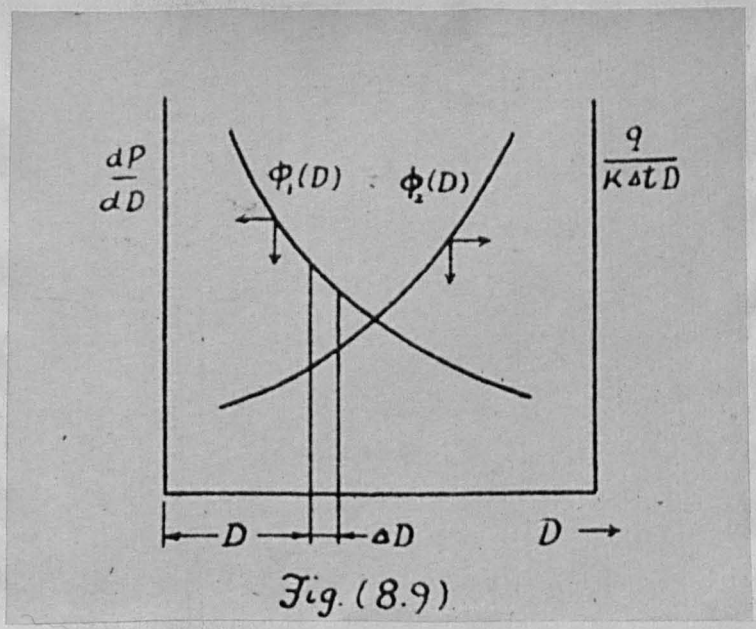


Fig. (8.9)

$\phi_1(D)\Delta D$ = the fractional area covered by drops having diameter between D and $D+\Delta D$.

For this size of drop, the heat transmission through each drop is

$$q = \phi_2(D)\, K \Delta t\, D \qquad \text{B.t.u./hr.}$$

where D = the diameter of drop, ft;

K = the thermal conductivity of water, B.t.u./ft-hr-°F;

Δt = the temperature drop from steam to the water side surface of metal plate, °F.

Hence the heat transmission through all drops of this size is

$$\Delta Q = \frac{\phi_1(D)\,\Delta D}{\frac{\pi}{4} D^2}\, \phi_2(D)\, K \Delta t\, D$$

$$= \frac{4}{\pi} K \Delta t\, \phi_1(D) \frac{\phi_2(D)}{D} \Delta D$$

B.t.u. per hr. per sq.ft. condensing surface.

The heat transmission through all drops having diameter between a and b is therefore

$$Q = \frac{4}{\pi} K \Delta t \int_a^b \phi_1(D) \frac{\phi_2(D)}{D} dD \quad \text{B.t.u.per hr.per sq.ft. condensing surface} \qquad (8.2)$$

Taking the metal plate as $\frac{1}{8}$ inch copper and the contact angle as 90°, $\phi_1(D)$, $\phi_2(D)/D$ and $\phi_1(D) \cdot \frac{\phi_2(D)}{D}$ were plotted in Fig.(8.10). The value of $\int \phi_1(D) \frac{\phi_2(D)}{D} dD$ for drops over 0.005" diameter was found by numerical integration to be 3070 ft^{-1}. Therefore, from eqn. (8.2)

$$Q' = \frac{4}{\pi} K \Delta t \times 3070 = 1570 \Delta t \quad \text{B.t.u. per hr.per sq. ft. condensing surface.}$$

which is the heat transmission through all drops over 0.005" diameter.

In so far as the distribution among smaller drops which amount to 45% total area is not known, it can be assumed as one of the following cases:

(1) all the 45% area unaccounted for be covered by drops of 0.005" diameter;

(2) All the 45% area unaccounted for be free surface;

(3) the distribution in the 45% area unaccounted for be assumed a straight line extension to the curve in Fig.(8.8)

Among the above three cases, (1) and (2) are designed to give limiting heat transmission rates in opposite directions, while (3) should be a fairer approach to facts.

Case (1) <u>All the 45% area unaccounted for be covered by drops of 0.005" diameter.</u>

The heat transmission through this 45% area is

$$Q_1'' = \frac{5.43\, K \Delta t D}{\frac{0.45}{\frac{\pi}{4} D^2}} = 2990\, \Delta t \quad \text{B.t.u. per hr. per sq.ft. condensing surface.}$$

To this is added Q' (the heat transmission through drops over 0.005" diameter) to give the total heat transmission through the whole condensing surface, thus

$$Q_1 = Q' + Q_1'' = (1570 + 2990)\Delta t = 4560\, \Delta t \quad \text{B.t.u./ft}^2\text{-hr.}$$

Hence h_{c1} = 4560 B.t.u./ft^2-hr-°F. (the combined heat transfer coefficient from steam to the water side surface of the metal plate.)

In eqn.(8.1), putting h_c = 4560, $\frac{k'}{x}$ = 21,100, gives the steam side coefficient

$$h_{s1} = 5800 \quad \text{B.t.u/ft}^2\text{-hr-°F.}$$

Case (2) All the 45% area unaccounted for be free surface

The heat transmission through this 45% area is

$$Q_2'' = 0.45 \frac{K'}{x} \Delta t = 9500\, \Delta t$$ B.t.u.per hr.per sq. ft. condensing surface.

The total heat transmission through the whole condensing surface is

$$Q_2 = Q' + Q_2'' = (1570 + 9500)\Delta t = 11{,}070\, \Delta t \text{ B.t.u/ft}^2\text{-hr.}$$

Hence $h_{c2} = 11{,}070$ B.t.u./ft^2-hr-°F. and from eqn.(8.1)

$h_{s2} = 23{,}200$ B.t.u./ft^2-hr-°F.

Case (3) The unknown distribution be assumed a straight line extension to the curve in Fig.(8.8).

There is only one straight line which can be drawn ih this way as it is required to satisfy the condition that the area under it be 0.45. With this assumption, the integral $\int \Phi_1(D) \frac{\Phi_2(D)}{D} dD$ in eqn.(8.2) was found to be 13,900 ft^{-1}, giving the heat transmission through the 45% area

$Q_3'' = \frac{4}{\pi} \kappa \Delta t \times 13900 = 7{,}100\ \Delta t$ B.t.u.per hr.per sq.ft. condensing surface.

The total heat transmission through the whole condensing surface is

$Q_3 = Q_3' + Q_3'' = (1570 + 7100)\Delta t = 8670\ \Delta t$ B.t.u./ft²-hr.

Hence $h_{c3} = 8670$ B.t.u./ft²-hr -°F, and from eqn.(8.1),

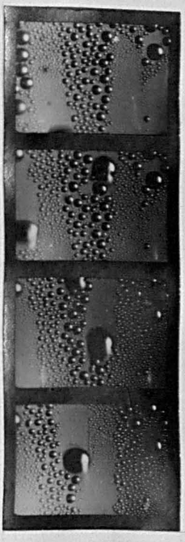
$h_{s3} = 14{,}700$ B.t.u./ft²-hr-°F.

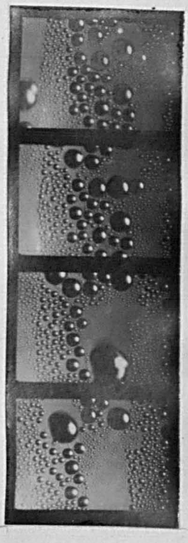
Compared with the steam side coefficients measured by various investigators (see P. 19), it can be concluded that when it is assumed, as in (1), that all the 45% area unaccounted for is covered by drops of 0.005" diameter, the steam side coefficient 5800 B.t.u./ft²-hr-°F is too low as might be expected. In (2) and (3) the coefficients 23,200 and 14,700 B.t.u./ft²-hr-°F fall within the range of experimental results.

Plate (8.1)

Plate (8.1)

Plate (8.1)


1
2
3
4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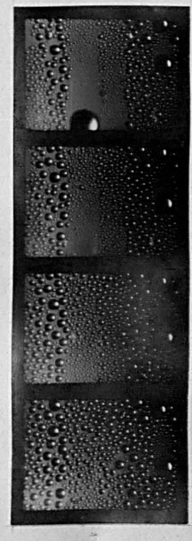
18
19
20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7
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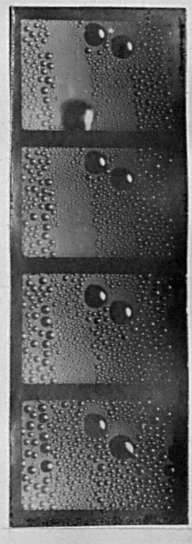
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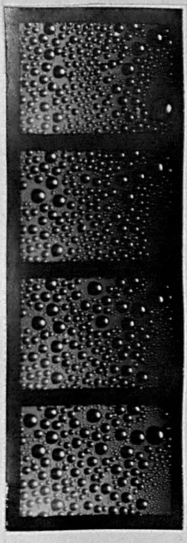
22
23
24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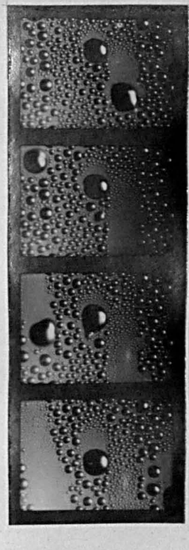
11
12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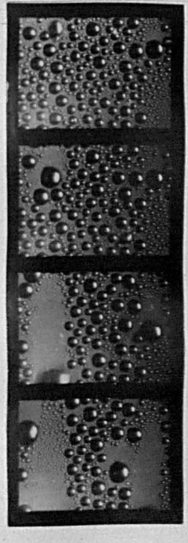
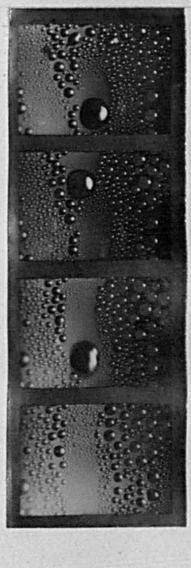
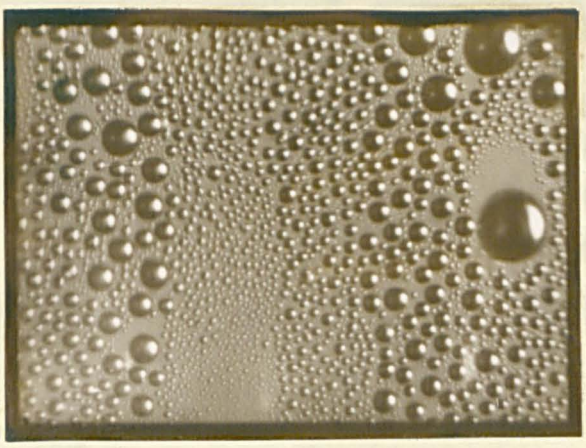
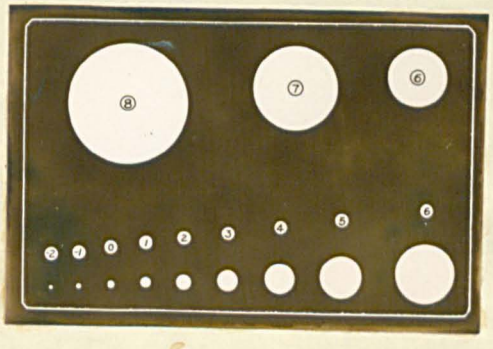

13
14
15
16


29
30
31
32



Plate(8.2) One Sample Frame on Which Counting Was Performed.
(Magnification 4.15x Natural Size)



Plate(8.3) The Graticule.

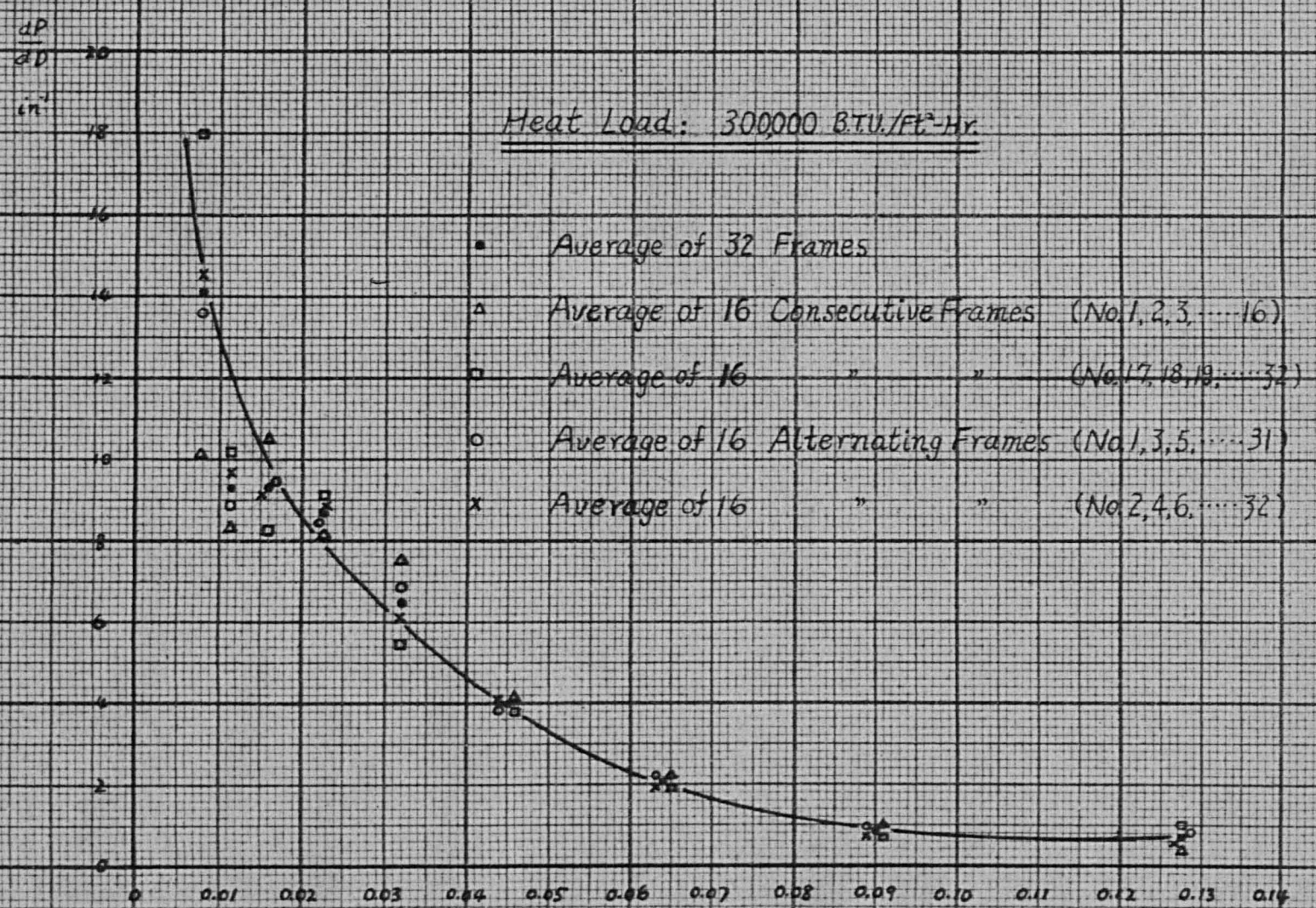
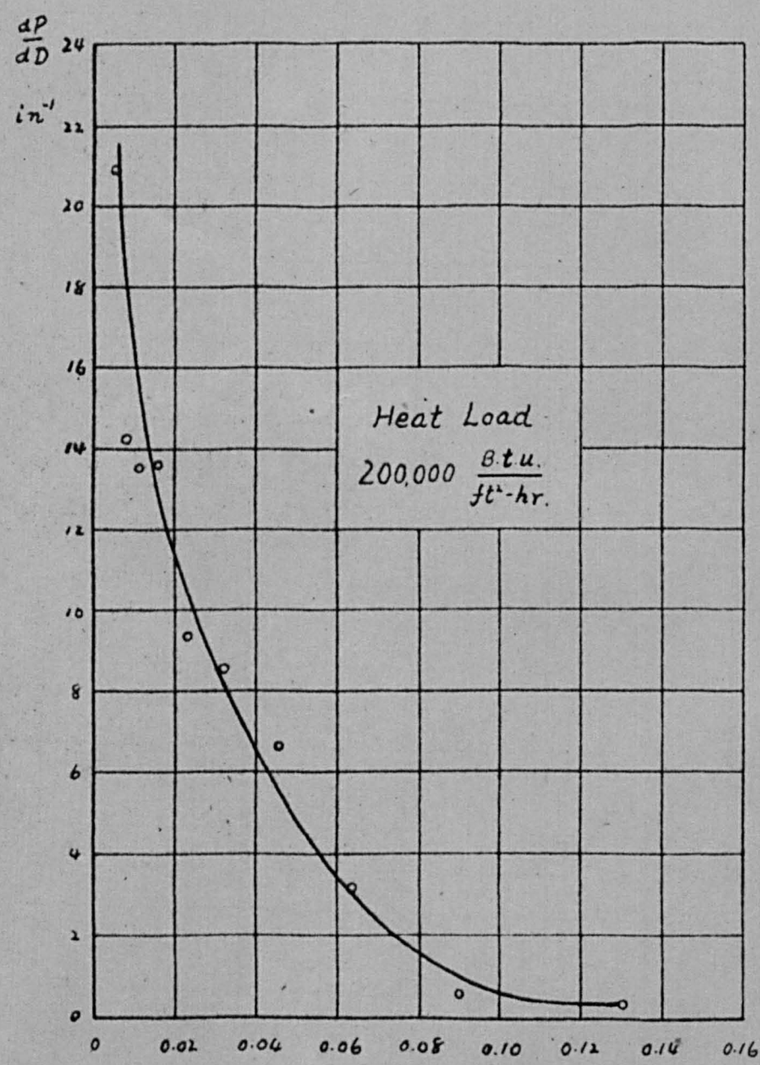
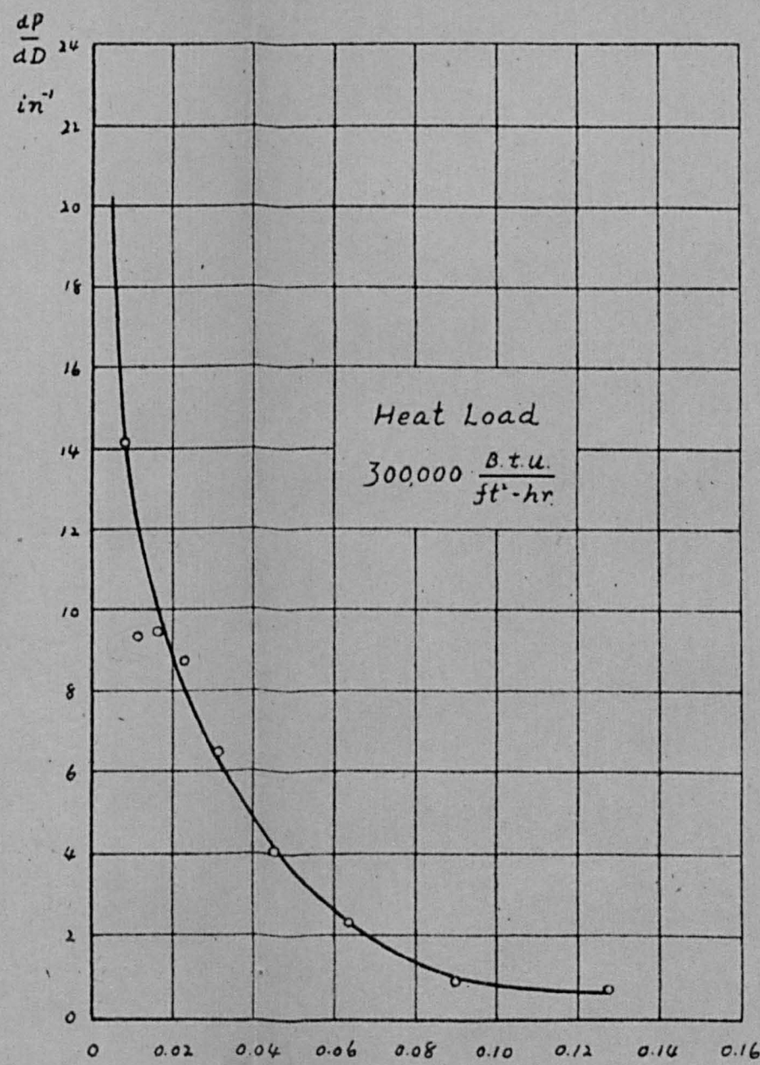

$\frac{dP}{dD}$ (in^{-1})
20
18
16
14
12
10
8
6
4
2
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
Diameter of Drop in Inches.
Heat Load: 300,000 B.T.U./Ft.²-Hr.
• Average of 32 Frames
△ Average of 16 Consecutive Frames (No. 1, 2, 3, ····16)
□ Average of 16 " " (No. 17, 18, 19, ····32)
○ Average of 16 Alternating Frames (No. 1, 3, 5, ····31)
× Average of 16 " " (No. 2, 4, 6, ····32)

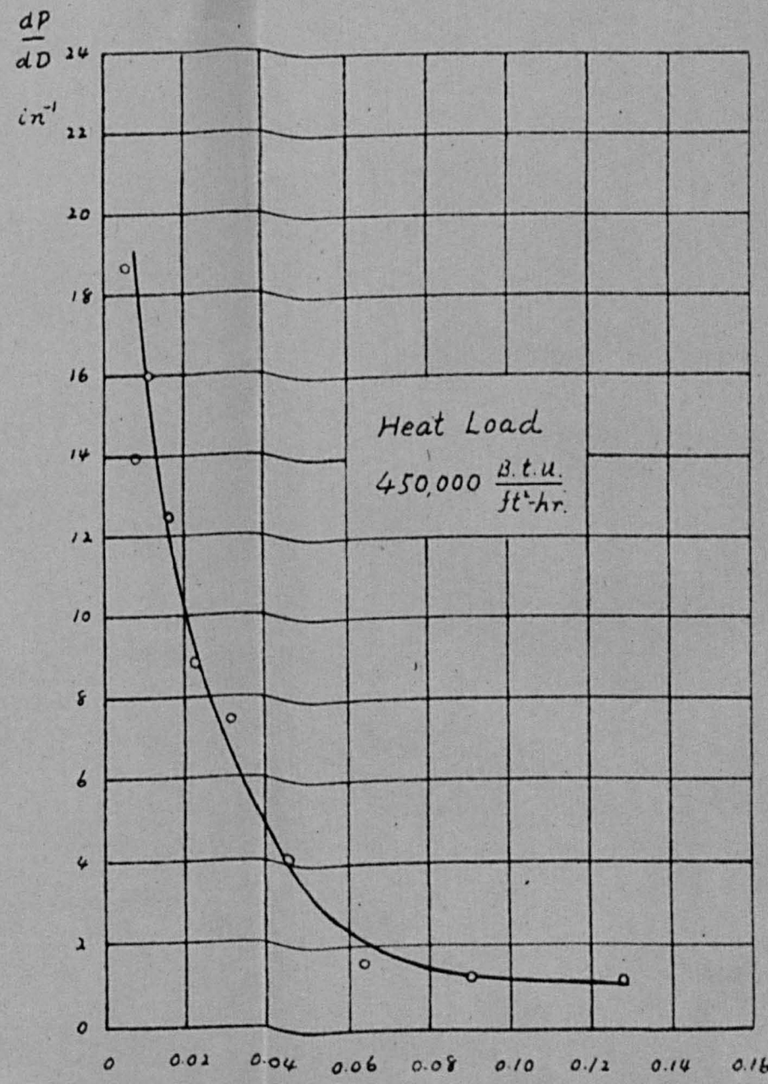
Fig. (8.6)



(a)



(b)



(c)

Fig. (8.7). Drop Size Distribution Curve for Different Heat Loads Plotted Separately.

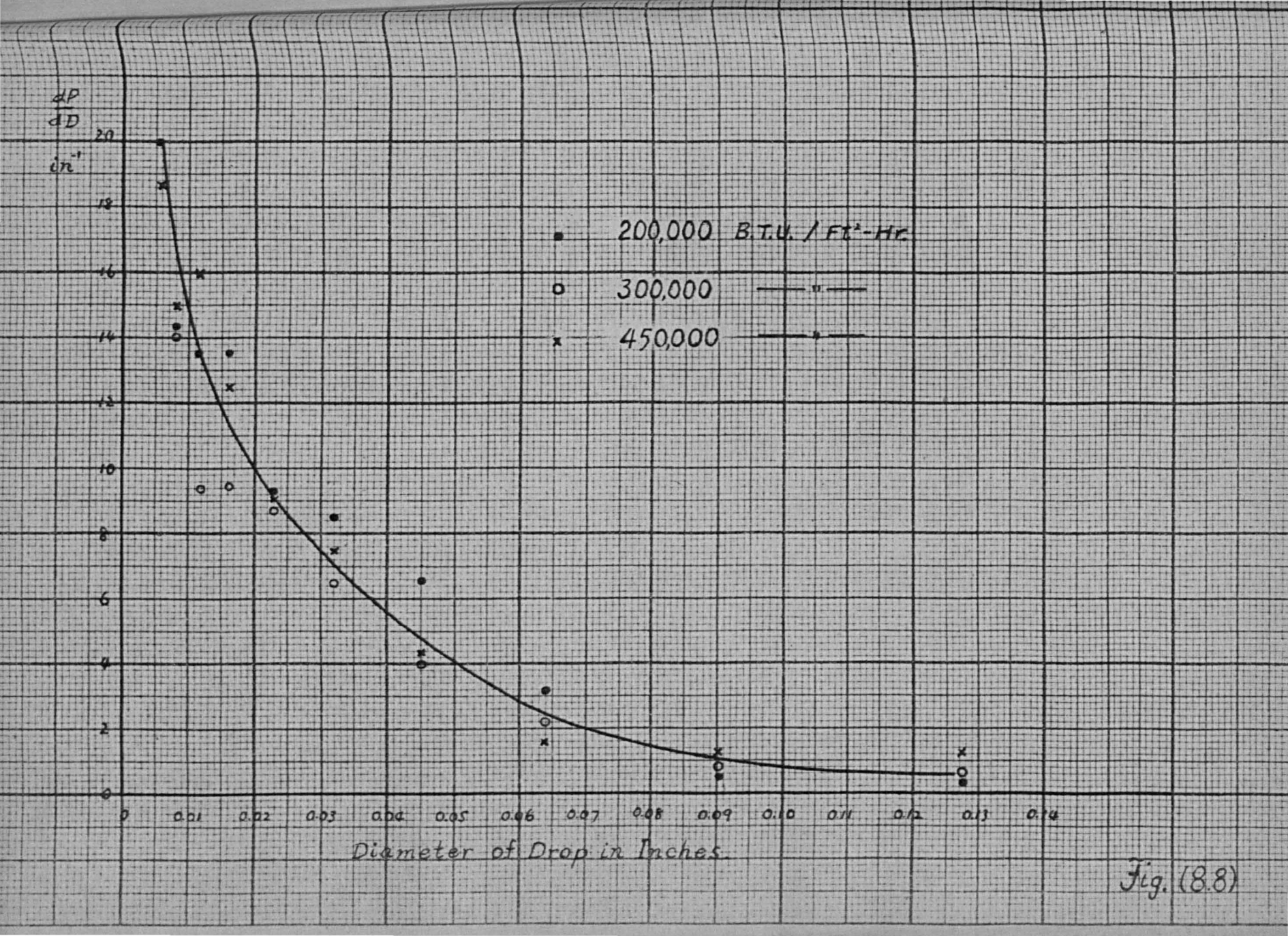

dP/dD
in⁻¹
20
18
16
14
12
10
8
6
4
2
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
200,000 B.T.U. / Ft²-Hr.
300,000
450,000
Diameter of Drop in Inches.

Fig. (8.8)

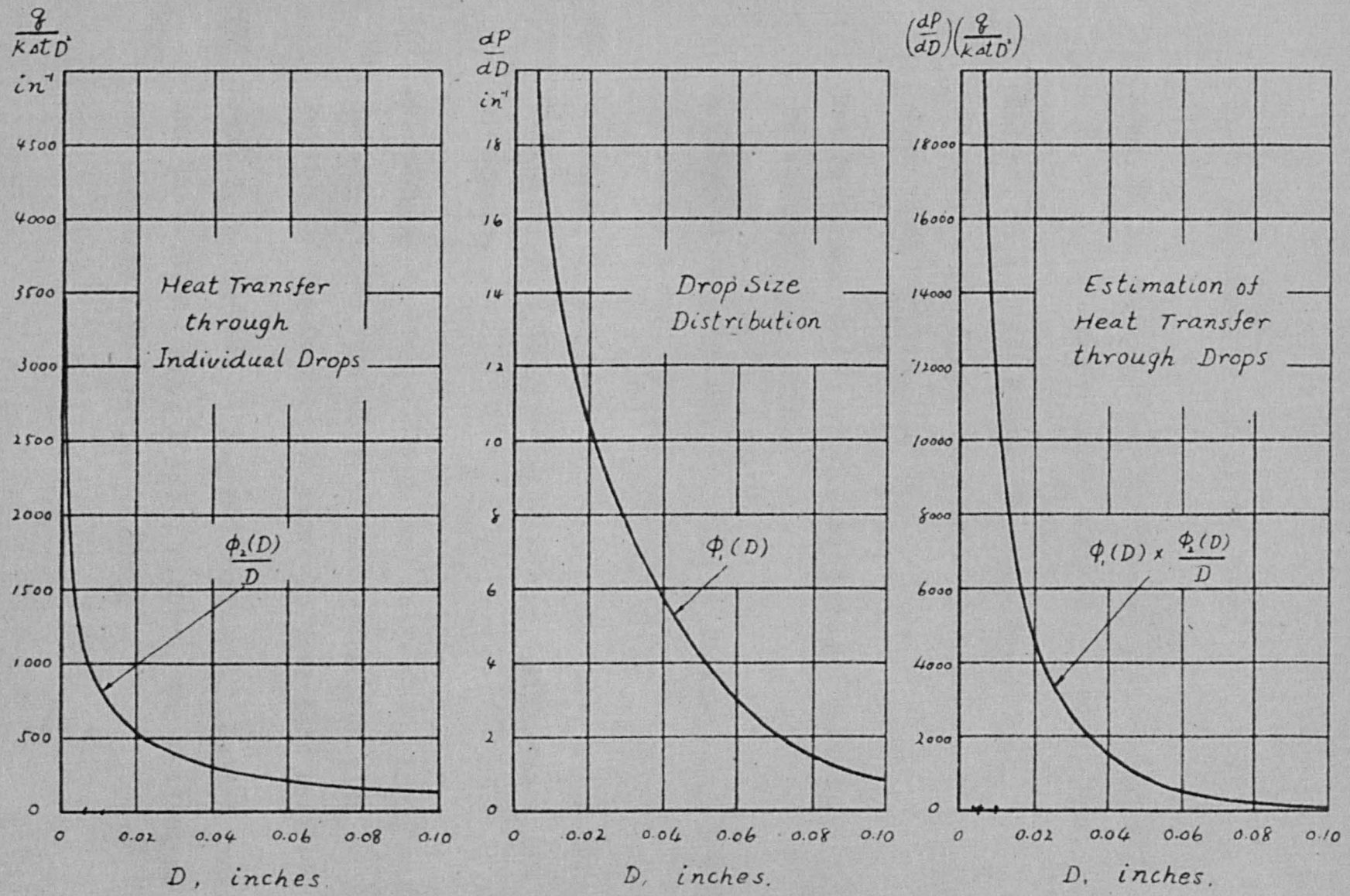


Fig. (8.10). Estimation of Heat Transfer through Drops.

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